THE MICROSCOPE

PART II

CONRAD BECK

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AN ADVANCED HANDBOOK

A SEQUEL TO "THE MICROSCOPE, A SIMPLE HANDBOOK"

BY

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PREFACE

THIS book supplements the information given in *The Microscope, a Simple Handbook.* It is an endeavour to explain the theory of the instrument in a manner that can be understood without reference to advanced mathematics. The general principles are explained without the elaborate scientific details that are necessary for the designer.

The practical worker may not be interested in the chapters which deal with the general optics of the lenses, but if he desires to use his instrument to the best advantage he should carefully read Chapters III, V, and VI, on Resolution, Glare, and Illumination.

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THE MICROSCOPE

CHAPTER I

THE GEOMETRIC OPTICS OF THE MICROSCOPE

Image formation—Focal length—Conjugate images—Simple lenses as microscopes—Magnified images—Magnifying power defined—Limited scope of single lenses—Compound lenses—Gauss method of dealing with compound lenses—Equivalent planes of single lenses and compound lenses—Compound lenses give additional power and greater working distance—Ramsden circle or eyepoint—Huygenian eyepieces explained—Tube length—Powers of eyepieces and object-glasses.

THE modern microscope is the most elaborate and perhaps the most interesting of optical instruments. Although at first sight it appears to be a particularly complex piece of apparatus it may be divided into a few groups of lenses, each of which has a particular function and each of which is provided with particular mechanical adjustments.

The purpose of most optical instruments is to form an image —in the case of a microscope a magnified image—and the first step in considering the action of an optical instrument is the investigation of the formation of an image.

Suppose that in Fig. 1 a diaphragm at O separates a brilliantly lighted space on the left-hand side from a dark chamber on the right. Suppose that in the diaphragm at O a fine hole is pricked, which, for argument' sake, is so small that it admits only one ray of light through it in every direction.

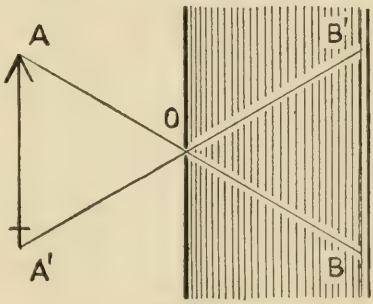


FIG. 1.

In geometrical optics light is considered to travel in straight lines, and an image or picture of an object A A′ outside the chamber will be seen at B B′ in the dark chamber if a white screen be placed there to receive it. That such an image is formed, is because only one ray of light can enter the dark chamber from

each point of the object; the only ray that can enter from the point A arrives at B, and no other ray of light can reach B. Every point of the object A A′ will have its corresponding point in the image B B′. If a point in the object is bright its corresponding picture will be bright, if the point A is green its image at B will be green, and so on.

It is not possible to make use of a pinhole sufficiently small to admit only one ray of light from each point, but it is quite possible to make a pinhole small enough to admit such a few that it will produce a fairly good image in a darkened room of a landscape outside. It will be, however, very faint, because the amount of light which is admitted by so small a pinhole is very small.

It will be observed that the image formed by a pinhole is inverted; the upper portion of the object is the lower portion of the picture—such must be the case from the nature of the projection.

A lens is a piece of transparent material such as glass, which has curved surfaces. It will produce an image if placed in the position of the pinhole because, although it will admit into the darkened chamber not one but a large number of rays from each point in the object, it has the power of bending all these rays so that they meet at another point in the image.

Figs. 2 and 3 show the two methods of formation of an image by a pinhole and a lens respectively.

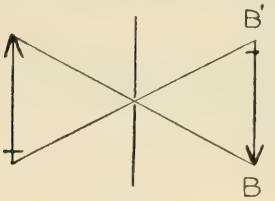


Fig. 2.

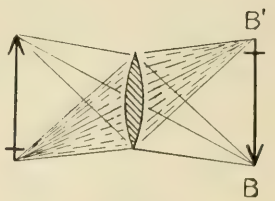


Fig. 3.

Unfortunately a single lens has many defects, and this power of accurately bringing the light to definite points can only be obtained by elaborate combinations which will be explained later.

In the case of the pinhole the picture is dim, in the case of the lens it is brilliantly illuminated; the larger the lens the more brilliant it will be. The most striking difference is that with a pinhole, no matter where the screen B B′ is placed, a picture will be seen; but with the lens, unless the screen is placed at one position, a clear picture will not be visible. Suppose the screen be placed at C C′ (Fig. 4) behind the position B B′ to which the lens converges the light, each point of the object will not be represented by a point but by a small patch. Each cone of rays

forming the image has spread out into a disc at the position C C′ Fig. 4. The image of the whole object will therefore be an indistinct haze consisting of a number of small overlapping patches of light.

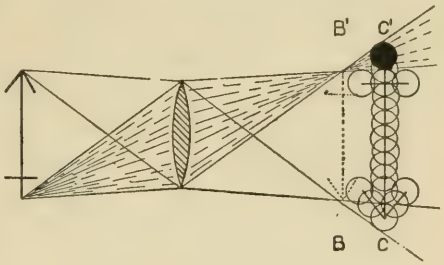


Fig. 4.

A lens therefore has a "focus." The original meaning of the word was burning place or altar. It was applied to a lens because it was found that if a lens was pointed to the sun, an object placed in the position where a sharp picture of the sun was formed could be set on fire, the rays of light and heat from the distant sun were concentrated at this point and the heat was sufficient to burn a hole in the object. The word Focus or Principal Focus is therefore now used to denote the position where a sharp picture of a distant object, such as the sun, is formed.

Conjugate Focus or Conjugate Foci are used to denote two positions, one on each side of the lens and at such distances from the lens that an object in one of them has an image formed of it in the other, thus the sun and the focus of the lens are a pair of conjugate foci. If a brilliant light were placed in the focus of a lens, its image would be formed in the position of the sun. The positions of the conjugate foci of a lens may be observed by unscrewing and making use of the larger lens of the low-power eyepiece of a microscope. If a lamp, or a well-illuminated object, be placed upon one side of this lens and a white screen upon the other, by moving the screen from place to place a position can be found at which a clear picture of the lamp or object will be formed upon the screen, If the object is shifted in position the picture on the screen will disappear, and the screen must also be shifted to some other position before a sharp picture of the object is again formed ; for every position in which the object is placed there will be a corresponding position where an image is formed. Any pair of positions, one of the object and one of its image, are called conjugate planes or conjugate focal planes. The investigation of the images or pictures formed in these conjugate planes constitutes the basis of the theory of most optical instruments.

When the object, as in Fig. 5 (1), is placed at a considerable distance on the left-hand side of the lens, its picture is close to the lens and is small. As the object is approached to the lens as in Fig. 5 (2), its image is further away and is enlarged, until when the object is brought still closer, as in Fig. 5 (3), the image

is still further away and is magnified several times. As the object is approached still nearer to the lens its image is produced further away, until a point is reached at which the image is formed at an infinite distance. If the object is brought still nearer to the lens its image cannot be formed at a greater distance than infinity. Mathematicians say that infinity has no limits, that eternity has no beginning, they discuss a fourth dimension and other problems that bewilder the mind of the mere man and certainly they have some justification. For if the image formed by a lens be carefully watched as the object approaches the lens, it is seen gradually to move further away till at a certain position of the object it reaches infinite distance, after which for a further movement of the object it leaps instantaneously from infinite distance on the one side of the lens, to infinite distance on the other, and steadily comes back to the lens from the opposite direction, as shown at Fig. 5 (5), but with a difference. Having

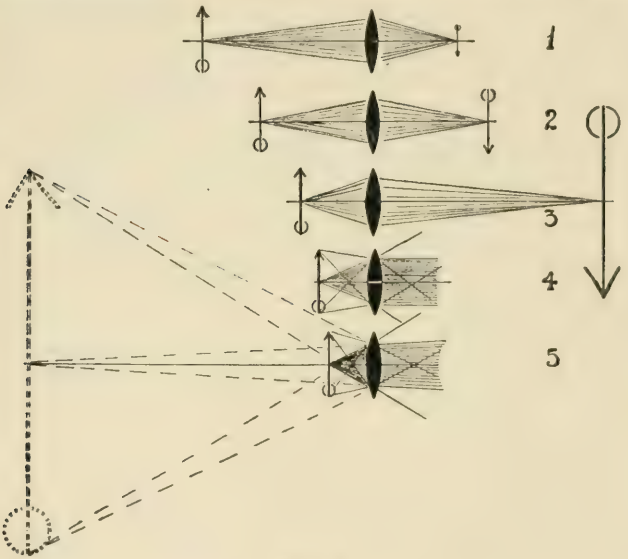


Fig. 5.

once been to infinity it returns as a ghost. It no longer actually exists in space, it cannot be demonstrated by means of a screen, but the light emerging from the lens behaves exactly as if this ghostly image really exists, and an eye placed in the line of sight on the right-hand side of the lens Fig. 5 (5) cannot tell from observation that this so-called virtual image is not a real object. When the image leapt from infinity on one side of the lens to infinity on the other, a further change took place during the process, it was turned upside down, for whereas it had previously

been an inverted picture of the object, it now becomes erect. Two useful laws of image formation are here demonstrated. Laws which in fact govern many of the simple problems connected with optical instruments.

1. If the image is on the opposite side of the lens to the object it will be the opposite way up or inverted. If the image is on the same side of the lens as the object it will be the same way up or erect.

2. The size of an object compared with the size of its image will be in exact proportion to the distance of the object from the lens compared with the distance of its image.

NOTE.—These two laws are expressed by the equation $\frac{x'}{x} = \frac{y'}{y}$ where x and x' are the distance of the object and image, and y and y' are the heights of the object and image above the axis. Signs being reckoned on ordinary geometric principles. If x is on the left of the lens and x' on the right, x will be minus in sign, x' will be plus, therefore, if y is plus, y' will be minus and the image will be inverted. The relative sizes of an object and its image being equal to their mutual distances from the lens is given by the same formula, and the simplicity of the expression $\left(\frac{x'}{x} = \frac{y'}{y}\right)$ renders it a useful note to stow away in one's memory.

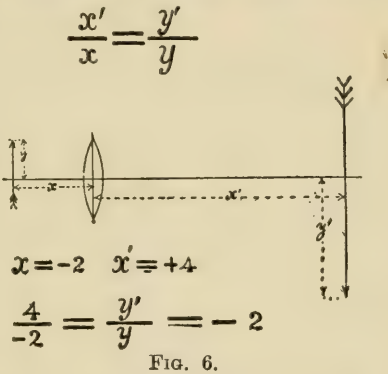


FIG. 6.

A microscope is an instrument which forms an enlarged picture of a small object, and an examination of the figure of conjugate images, Fig. 5, shows three distinct methods of making a microscope with a single positive lens.

(*a*) If a screen be placed where the image is formed in Fig. 1 (3) the enlarged picture will be seen upon it. A well-known example of this is the magic-lantern. The name of microscope is not applied to a lantern, because it is not generally used to investigate objects so small that they cannot be seen with the naked eye, but merely to render a diagram or picture, that can be readily observed by a single observer, large enough to be seen by a number. This first method of making a microscope has its good points, it will give any degree of magnifying power provided that sufficient space is available, and more than one observer can see the picture; the image has only to be projected further away to increase its size, but it suffers from the practical disadvantage that the object must be illuminated with an intensely brilliant light. The diagram (Fig. 7) indicates at A a screen, S, receiving the picture of a point of light focussed upon it by

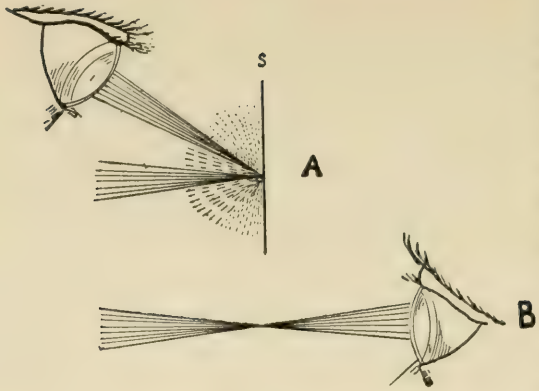


Fig. 7.

means of a lantern. The effect of the screen is to distribute the light thus received in all directions so that the quantity conveyed to it in a solid cone of, say, one degree is reflected in a solid cone of 180°, and the light which can be collected by the eye of a single observer is perhaps not more than 1/100,000th of the total quantity. This form of microscope is therefore unsuitable for giving high magnifying power.

(*b*) The difficulty of insufficient light may be overcome if a second method is used, in which the screen is removed and the eye is placed behind in the direct line of the incident light. The image exists in space; whether the screen be there or not, it is formed by the lens and not by the screen. It may be examined as if an enlarged copy of the object actually stood where the screen was placed. Fig. 7 shows at (A) an image which has been formed by a lens on a screen S being observed by the eye. Fig 7 (B) shows the screen removed, and the eye examining the image from behind the position of the screen in the direct line of the incident light. But there is a difference in the amount of the object that can be seen at one time. If an actual object A B C (Fig. 8) is examined, every point on that object is reflecting light in all directions, and an eye placed at E can collect a pupil full of light from every point on the object, and thus see the whole area at once; whereas if an image

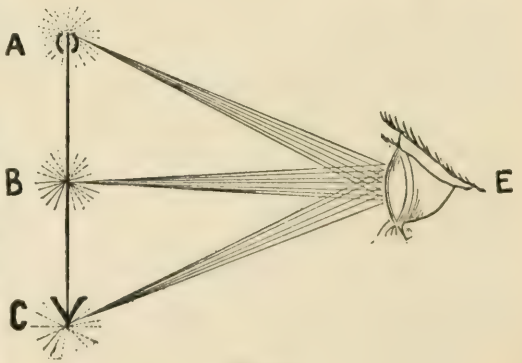


Fig. 8.

A′ B′ C′ (Fig. 9) is being formed by certain definite rays, an eye placed at E can only see the centre of the picture, and must be moved to D to see one end or to F to see the other extremity.

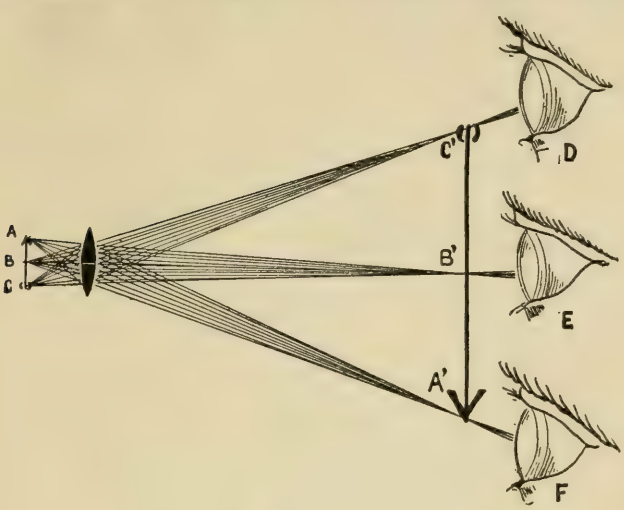


Fig. 9.

Thus the second form of instrument has only a small field of view; so small a portion of the picture is seen at one time, that although in combination it forms the basis of the present compound microscope, it was never developed as a simple instrument. This means of obtaining a high magnification with a pocket lens is seldom realised. The difficulty in its use consists

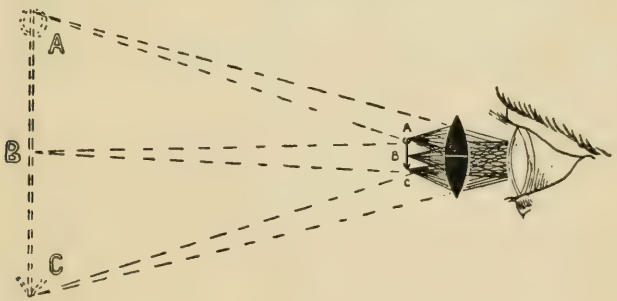


Fig. 10.

in the fact that the lens must be placed a long way from the eye. The eye could not see the image formed at C′ B′ A′ (Fig. 9) unless it were placed much further to the right-hand side than is indicated in the figure. A pocket lens held at arm's-length can

be made to give two or three times its normal magnifying power on this principle, but its field of view is very small.

(*c*) The third form of microscope (Fig. 10) is the ordinary magnifying glass. In this case the object is placed sufficiently close to the lens to produce a virtual or ghost image some way

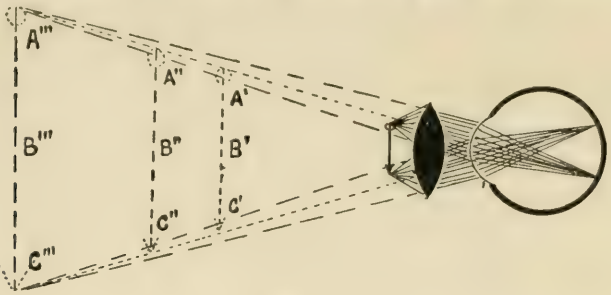


Fig. 11.

in front of the eye; it also requires the eye to be placed in the line of sight, but it largely overcomes the defect of the limited field of view, for provided the eye be placed sufficiently close to the lens it can gather in quite a large proportion of the light from the virtual image A′ B′ C′, and can see the whole of the object. It also gives an erect instead of an inverted picture.

This type of microscope has an important characteristic. It gives only one magnification. In the two previous forms a different degree of magnification could be produced by altering the position of object and lens. Here one lens gives one magnification. If the diagram (Fig. 11) be referred to, it may be objected that by slightly altering the position of the object one can produce its image at different distances, either at A′ C′ or A″ C″, and that as this image is further from or nearer to the lens, so it is larger or smaller. That is so; but as this image goes away from the lens, so also it goes further from the eye, and though in

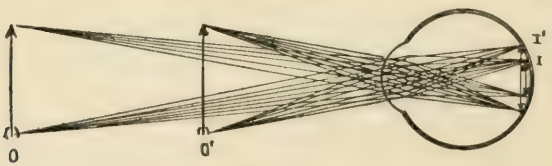


Fig. 12.

reality it is larger, yet, being further away, it appears smaller, and no alteration in its size is visible.

The diagram (Fig. 12) will recall the fact that the reason why an object at a distance looks smaller, is that its image on the retina actually is smaller. The eye is a form of camera;

an object at O, which is seen at I on the retina of a certain size, will be seen twice as large if it be brought to O′, twice as near; and thus the reason that a distant object looks small is not a mental association, but a solid fact, and shows that the image is always the same size on the retina of the eye if it subtends the same angle.

The position at which the virtual image seen through a lens actually does exist is at present undetermined, and probably differs with different individuals.

The question of magnifying power may now be investigated. The first point to be clearly borne in mind is that with the microscope magnifying power is always expressed in linear diameters. It may be true that a carpet 12 feet square (Fig. 13) will cover 144 tiles which are one foot square, yet it has only a linear size or length twelve times that of the tile. A room which is 12 feet square and 12 feet high will contain 1,728 boxes 1 foot cube; it has only a linear size twelve times that of the box. The magnifying power of a microscope is denoted by linear diameters; by the relative lengths of object and image, and not by their relative areas or cubic capacities.

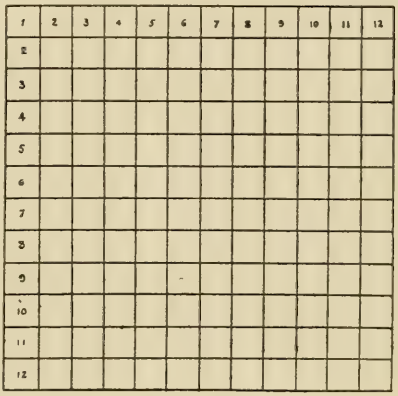


FIG. 13.

Magnifying power is not so easy to express as might appear at first glance. If an actual image of an object is formed on a screen as in the case of a lantern or projection microscope, no difficulty presents itself; the diameter of the object can be measured in inches or millimetres; the diameter of the image can also be measured and their relative size can be ascertained. But where no actual image exists, where it is only a virtual or ghost image that cannot be got at in order to measure it, the question is not so simple. It can be calculated, but to do this we must either consider it as subtending an angle or we must assume that the virtual image is at a certain distance from the eye. A difficulty arises in conveying a correct idea of the size of any object which is inaccessible. It is sometimes said that the moon appears to be the size of a plate, a Dutch cheese, or a piece of chalk. None of these give an adequate idea of its apparent size. It will be found that a good-sized pea, held at arm's-length, will obliterate it, and it is evident that in order to explain the apparent size of a virtual image that cannot be actually measured, it is

necessary to suppose that such virtual image exists at some definite position. It means nothing to say that the image of some object when seen through a simple microscope is 3 inches diameter; 3 inches at a distance of 100 yards will appear as a point, whereas 3 inches at arm's-length would be a perceptible size; neither is it any good to say that it looks ten times the length of the original object, because the original object looks different sizes at different distances from the eye. It is necessary to say it looks ten times the size that the original object appears when that is placed at some definite distance from the eye. The important thing is that the same distance should always be used. It makes no difference what distance is selected for the purpose. It is fortunate that the distance which was originally selected has been universally adopted, and is not likely to be changed. The near point of vision is somewhere between 8 and 12 inches, and with this consideration in view the distance of 10 inches from the eye has been selected as the position at which it is assumed that the virtual image formed by a microscope exists.

Now what does it mean when we say that a simple microscope magnifies five diameters? It indicates that if an object 1 inch in diameter appears a certain size to the naked eye when placed at a distance of 10 inches, the microscope will make it appear as if it were an object 5 inches in diameter placed at 10 inches from the eye. It is important to understand how this affects the question of magnifying power.

Suppose a diagram of fine lines is being examined, and it is found that a series of lines 100 to the inch can be readily seen when they are placed 10 inches from the eye, a microscope magnifying 5 produces a picture in the eye five times the size of that produced by the diagram when held at 10 inches, and consequently lines 500 to the inch are visible. That is, a magnifying power of five allows five times the amount of detail to be observed compared with that which is seen when one examines objects at a distance of 10 inches. Many observers, however, and especially those who are short-sighted, are in the habit of examining minute objects much closer to the eye, and bringing the object much closer to the eye will mean that a larger picture is formed on the retina. Some very short-sighted people can place an object as close as 2 inches from the eye and thus see five times as much as at 10 inches; consequently they can see 500 lines to the inch. It would appear to such an observer that the microscope magnifying five times would show nothing more than they could see with the unaided eye. As a matter of fact, such an observer would obtain some magnification, but it would be considerably less than that gained by the normal eye. Nevertheless, the microscope is said to magnify five times, because it is considered that objects are generally examined at 10 inches

distance, and the picture formed will be five times the size of its original if placed 10 inches away. For this reason disappointment is sometimes experienced at what appears to be the small magnifying power of a pocket lens.

The simple microscope in the form of a pocket lens has defects. These defects can be cured, as will be seen later. It can be made to give good defining power. It has a fairly large field with moderate magnification. Its magnification depends on the focal length of the lens and that only. Why not make the focal length of such a lens as short as is required and get any magnifying power that may be desired ?

The answer is that a simple microscope has certain restrictions which render such a method impracticable for high magnification. First, the object to be examined has to be placed too close to the lens. Secondly, lenses would have to be made microscopically small. A single lens with a magnifying power of about 1,000 could not be made of larger diameter than 1/50th of an inch. The reason of this is because the focal power of a lens depends on the radius of the curve to which it is ground. Fig. 14 shows at 1 a plano lens of moderate power. By making

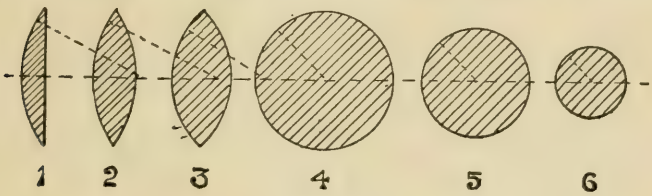


FIG. 14.

it double convex, putting the curve on both sides as at 2, the power is doubled ; increasing the curvature at 3 still further increases the power, till eventually it becomes a sphere, as 4. Here the power can only be further increased by making the sphere smaller, as 5 and 6. No curved lens can be made larger than a sphere, and therefore, if a lens has a radius of 1/100th of an inch, it cannot by any means be made larger than 1/50th of an inch.

A small lens of the kind used as a pocket magnifier can transmit but a small bundle of light, and the pupil of the eye, instead of being filled with light, receives only a minute fraction of the amount required to give a brilliant image. Thirdly, the eye cannot be placed with comfort nearer than about half an inch from the lens on account of eyelashes and eyelids, and although this may not matter with a low-power lens, such as 2 (Fig. 15) with a high power it seriously restricts the field of view. The diagram (1), Fig. 15, shows that the higher the power of a lens producing a highly magnified image, the nearer the eye must be

in order to see more than the centre of the object, because the light with a high power is emerging at a greater angle and these angular rays will not enter the eye unless it is almost in contact with the lens.

This is rendered still worse by the fact that thick combinations of lenses must be used to correct the aberrations, which renders it still more difficult to place the eye near to the projection centre of the system. Thus a limit of usefulness is reached for the simple microscope. It is serviceable for magnifying powers up to about 15 to 20 diameters.

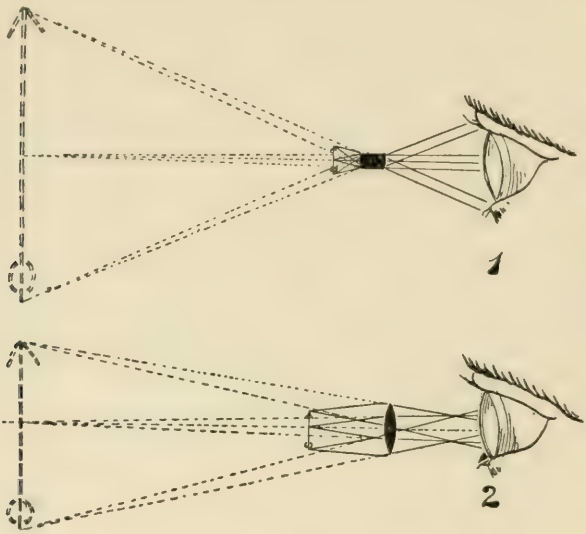


Fig. 15.

The three radical objections to a high-power simple microscope are:—

1. The closeness of the object to the lens.
2. The impossibility of getting magnifying power except with minute lenses.
3. The restricted field of view.

In order to investigate the methods by which the compound microscope overcomes these objections the Gauss method of dealing with combinations of lenses is of assistance.

By the use of Gauss's elegant device the action of a complicated combination of lenses can be grasped with almost the same ease as that of a simple lens.

The substance of this theory may be explained as follows. Suppose A, B, and C (Fig. 16) represent a set of lenses forming a compound optical instrument. In the upper half of the dia-

gram is shown the course of a ray of light emerging from a point x, which is refracted or bent at each lens, and finally arrives at the point x'. To trace the course of such a ray through the twelve or fourteen lenses which sometimes compose a microscope would be a tedious and difficult operation, and, what is worse, the performance of the microscope as a whole would be almost impossible to comprehend. The size and position of images formed by compound instruments are difficult to ascertain if every individual lens has to be treated as a separate item. But Gauss has shown that, under certain conditions, any complex system of lenses may be replaced by a single so-called equivalent lens, and that the effect produced by this compound system may be studied by supposing it to be for the time being a single equivalent lens. The idea will suggest itself, that if this is so, why

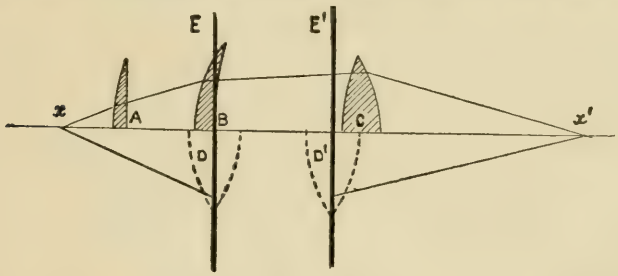


FIG. 16.

use compound systems at all; why not employ the equivalent lens instead? Well, for this reason, that the equivalent lens, in order to personate a numerous set of lenses, must be endowed with the peculiar quality of being in two places at once. No single lens placed in one position will do the work. It must have the power of being in one position, D, to receive the light, and in the second position, D′, to discharge it. In practice a dual personality cannot be bestowed upon a lens, but for investigation it is quite an easy matter to imagine such a rapid shift in its position.

The system of three lenses, A, B, and C, in the diagram may be represented by a so-called equivalent lens, D, which exists at a position known as the first equivalent plane, E, for receiving rays, and at the second equivalent plane, E′, to discharge them. The equivalent lens has a particular focal length or power according to the system it is to represent, and that is called the equivalent focus, which is indeed the true focal length of the compound system. It will then for many purposes be possible to forget the complicated system and work out the problems of image formation, just as would be done with a plain lens, and with the same simplicity except for this shifting of its position from one equivalent plane to the other. In the diagram the

equivalent lens, D, must be considered as existing at E, to receive the light from x, and as existing at E′ to discharge the light to x'.

All measurements with reference to light entering the system must be made from E ; all measurements with reference to light emerging from the system must be made from E′ ; and the numerous refractions which take place at the various lenses may be considered as being represented by two single refractions, one at E, and the other at E′. Every combination, however complex, provided it has a focus at all, has an equivalent lens and two equivalent planes, and the equivalent focal length and the position of the equivalent planes having been found, the whole may be dealt with, and investigated.

The positions of these two equivalent planes, which vary in a most surprising manner according to the construction of the lenses, forms the key to the action of the instrument. This elegant theory has, however, limitations which must be understood. It can only be applied to lenses as regards their central portions. The edge of a large lens, as will be seen later, does not act in the same manner as its centre, neither do the rays of light that pass obliquely through a lens behave in the same manner as those which pass through it direct. The Gauss theory is only true for central direct beams of light. The microscope deals with very wide angle beams of light, and beams far from its central axis, as well as the central direct ray, so that it would appear that the Gauss theory can be of but little practical service for investigating microscopal problems. But the endeavour of the optician in manufacturing the instrument is to so arrange and correct his lenses that their edges, taken in combination, will act upon the light in exactly the same manner as their central portions, and so that they will act upon the oblique in a similar manner to the direct rays. This he actually accomplishes to a large extent, and thus, although the Gauss theory cannot be strictly applied to the individual uncorrected portions of the instrument, as soon as the corrections have been made, the compound system can be considered as a more or less perfect Gauss system. The optician cannot employ the method in making his various corrections, but, once the instrument is formed, the problem of magnifying power, illumination, and other questions affecting its general behaviour can be investigated by this means. There are certain conditions of the Gauss theory which cannot be fulfilled quite accurately, and to this extent results obtained with the simple method may require correction, which fortunately will be small with a well-corrected system.

If the method of investigation be now applied to the consideration of the simple microscope, the methods by which its disadvantages can be removed may be studied. The magnifying power of a single lens is expressed by its focal length. The magnifying power of a combination of lenses is expressed by the

focal length of its equivalent lens. The focus or burning point is the position where the rays of the sun, or any other distant object, shining through a lens meet in a point; and the equivalent

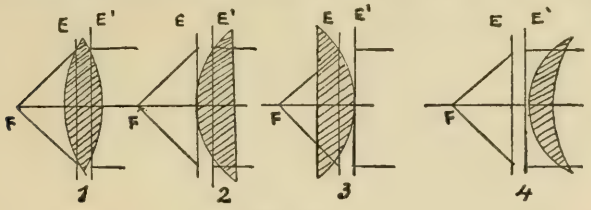


FIG. 17.

focal length is the distance from the focus to the equivalent plane belonging to that side of the optical system. The focal length of a system can be shortened, and the power thus increased by altering the curvature of the lenses, but as has been shown this involves practical disadvantages, one of which is that the object must be placed very close to the lenses. Gauss showed that the position of the equivalent planes could be altered to an almost unlimited extent by altering the shapes and positions of the lenses without affecting the power of the instrument, and therefore that the position of the focus of a system can be altered without altering its focal length or power. The equivalent plane, together with the focus, can be pushed forwards or backwards. The Gauss equivalent lens is assumed to have no thickness, and when a lens has any considerable thickness it must be treated as a complex optical system with an equivalent thin lens and equivalent planes. The position of the equivalent planes of even a single thick lens varies to a considerable extent, as shown in Fig. 17. The focal lengths of these lenses are all the same, but owing to differences in shape the equivalent planes E E′ are in different places, and thus to examine an object placed in the focus, F, using such lenses as simple microscopes, the object need not be placed so close to the surface of lens 4 as is necessary with lenses 3, 2, or 1. A gain in working distance is obtained. For reasons that will subsequently appear, a microscope object-glass must be made of a number of lenses close together, and in a combination of lenses the position of the equivalent planes varies to a far greater extent than in a single lens. Fig. 18

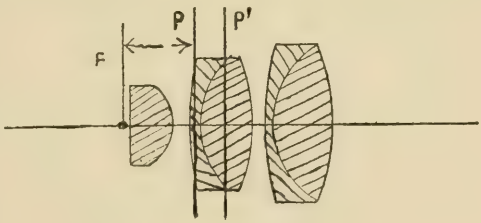


FIG. 18.

may be taken as an example of a common type of high-power lens. The focal point where the object must be placed, if the lens system is to be used as a simple microscope, is practically on the surface of the front lens, and it will thus be seen that as a means of curing the defect of closeness to the object which we have seen to be inherent in the simple microscope, a series of lenses close together may not be of much assistance. Therefore it will be well to consider what happens to the position of equivalent planes when lenses are separated. The results of such an investigation are very remarkable. In a paper read at the Optical Convention of 1905 [1] the matter was investigated, but Fig. 19 indicates the astonishing way in which

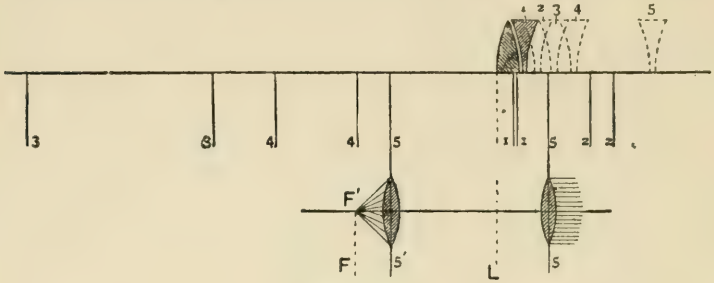


Fig. 19.

the positions of the equivalent planes of a lens system are altered when two lenses are separated. The figure shows above the horizontal line two lenses, one positive and one negative. Where the two are close together at the shaded position 1, the position of the equivalent planes are shown below the line in the diagram at 1.

If the positive lens remains stationary and the negative lens be moved to the positions 2, 3, 4, 5, indicated by the dotted lines in the upper half of the diagram, the positions of the corresponding equivalent planes are shown in the lower part of the diagram marked 2, 3, 4, 5.

At the final position in the diagram 5, 5′, where the lenses are separated by the greatest interval, the action of the complete system will be as if an equivalent lens of the focal length, F 5′, were placed first at 5′ to receive the light, and then at 5 to discharge it into an observer's eye. Thus it will be seen that the complete system has the magnifying power of a single lens placed at 5′, but the object can be placed at the great distance, F L, away from the surface of the positive lens, and the difficulty of the closeness of the object to the lens is overcome.

Several hundred years ago microscopes were made with

[1] "The Consideration of the Equivalent Planes of Optical Instruments," by Conrad Beck. *Transactions of the Optical Convention*, 1905.

separated lenses which gave this increase of so-called working distance, making it possible to use high powers conveniently; but their inventors, who produced their instruments by experiment, had no notion as to why the result was obtained.

The second defect of the simple microscope was seen to be the practical difficulty of making sufficiently powerful single lenses. To overcome the defect, the first expedient to suggest itself would be to make an enlarged image with one lens, and then to further enlarge that image by examining it with a second lens, then a third, and so on. This has been the method which was

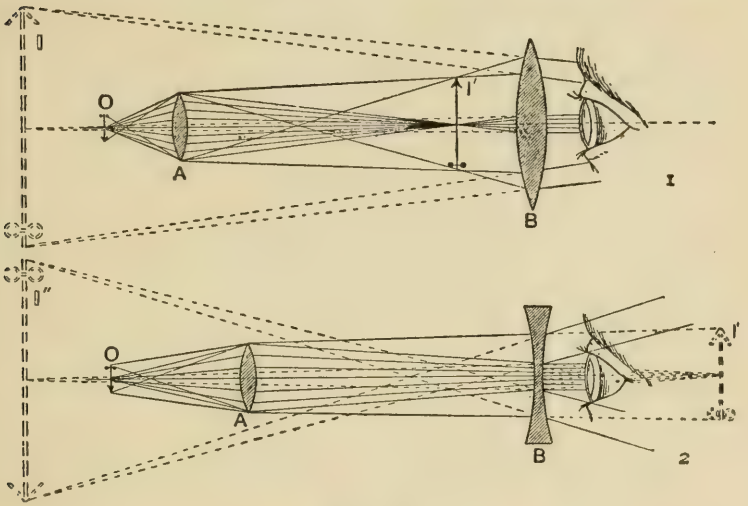


Fig. 20.

actually employed to produce what is now known as a compound microscope. By this means, of combining two simple microscopes into one instrument, as much magnifying power can be obtained as can advantageously be used. The one, called the object-glass, because it is nearest to the object, is used to project an image into space behind it, as in Fig. 5 (3), and the other, called the eyepeice, as being close to the eye, is in principle nothing more than a simple microscope for magnifying the image produced by the object-glass, as Fig. 5 (5).

The simplest form of compound microscope, an done which was actually constructed some hundreds of years back, consists of two simple convex lenses used in exactly this manner. The modern instrument is essentially of the same type, although the object-glass consists of a number of lenses combined, and the eyepiece consists of at least two components.

The object-glass must always be a positive lens, but the eye-

piece may be made upon two designs. It may be a convex or positive lens in principle—that is, a magnifying glass as in Fig. 5 (5)—or it may be a concave or negative lens. This will appear surprising, because when investigating concave lenses we have been accustomed to believe that they are incapable of producing images at all. Any positive lens will give us an image of the sun, and may be used as a burning-glass, but we may try in vain to obtain an image with a negative lens. The reason for this is because all the light given off by objects in nature is divergent; it is spreading out from points, and a positive lens is required to form an image with divergent rays. If converging rays were to be met with in nature negative or concave lenses could form images. Fig. 20 illustrates how images are formed by the object-glass in both cases: by a positive eyepiece lens in the first, and a negative in the second diagram.

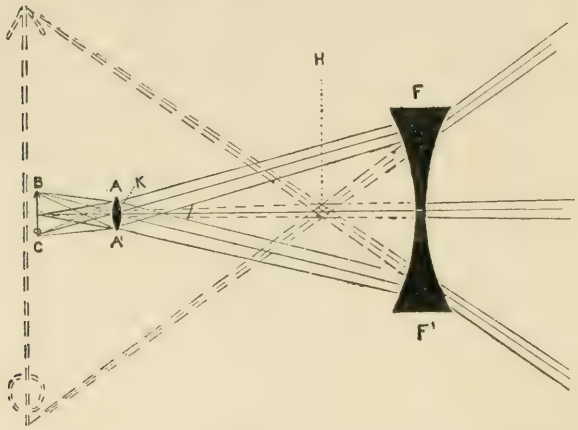


Fig. 21.

In the case of 1 the positive eyepiece B forms a virtual image of the rays diverging from the image 1′. In the case of 2 the negative eyepiece is placed so as to intercept the rays at a point before the image 1′ is formed, at a position where the rays are converging, and can consequently form a similar virtual image at 1″.

Both these combinations give the same magnifying power, but it will be observed that when the negative eyepiece is used the object-glass is further away from the object than when the positive eyepiece is used. So that as far as magnifying power is concerned it is as good as the positive eyepiece, and as to the working distance or distance of the object from the lens it is much better. It also does not invert the final image, so that it would appear to be the better eyepiece to adopt, but its disadvantage lies in the fact that only a minute portion of the object

is seen at once. It has a very small field of view. Nevertheless, in dissecting microscopes where an erect image and large working distance are required, it is still in occasional use under the name of the Brücké lens. Neither of these forms have completely satisfied the requirements of giving a large field of view.

To thoroughly understand this question it will be necessary to consider what is the condition required in order to give a large field. This condition is that rays proceeding from all parts of the object must be collected into a sufficiently small area to enter the pupil of the eye, and that this area must exist in some position where the eye can be placed. The case of a negative eyepiece will first be considered.

The diagram (Fig. 21) shows that here the light after having once entered the microscope continues to expand, and there is no collecting of the rays throughout the entire course. It is

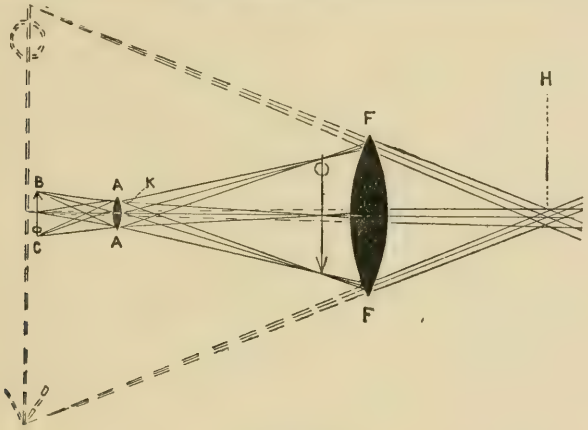


Fig. 22.

true that all the rays pass out of the instrument, also they emerge as if they had all passed through a small circular space at H. The rays both from the points B and C, and in fact all other parts of the object, appear to have passed through this area ; and if the eye could have been placed at such a point, the whole of the object would be seen, but as H is inside the instrument this is impossible.

A little consideration will show that this disc H is a conjugate image of the aperture, or more correctly the back equivalent plane of the object-glass A A′, as the three rays which pass through the centre of the lens aperture at K meet again at H. This conjugate image of the aperture of the object-glass is called the Ramsden circle, or the eyepoint, and in order that a microscope should have a large field this must exist outside the instrument in some position where the eye can be placed.

Let us now consider the case of a positive lens. The action

of such a lens is shown in the diagram (Fig. 22). A virtual image of the object is formed in the usual way and the light is at the same time focussed down to a small area H outside the instrument, the Ramsden circle at H being a conjugate image to the aperture A A′. As the object-glass is in most microscopes at a considerable distance from the eyepiece the Ramsden circle will be formed near the focus of the eye lens, and its size will be in the ratio of the distance of the object-glass A F, compared to the focus of the eyepiece F H, and will under ordinary circumstances be an image reduced in size. This is exactly what is required, as the pupil of the eye is small and cannot receive a large bundle of rays.

A positive eyepiece is therefore the best form, but such a positive lens has to be very large in order to collect the whole cone of light. Large lenses are not capable of being made of high power because their curvature cannot be great. To overcome the difficulty the Huygenian eyepiece consisting of two lenses, one large and one small, was devised. The total power is nearly as great as the smallest of its lenses, and its light-collecting capacity is much greater than its largest lens. This eyepiece might be investigated by examining one lens at a time, but the problem can be much more easily dealt with when examined by the Gauss method of an equivalent lens to represent the complete system. In fact this will prove to be a good illustration of the advantages of using this system for broad optical problems.

The focus of its equivalent lens and the position of its equivalent planes must be worked out by the ordinary formulæ or obtained by experiment. These planes will be found to occupy curious positions; they are crossed over, the equivalent lens exists at E to receive the light coming from the object-glass on the left-hand side, and must be pushed backwards to E′ to discharge it into the eye (Fig. 23).

The upper part of the diagram shows the actual course of the rays through the Huygenian eyepiece, the lower portion shows its equivalent lens made just large enough to receive the whole cone of light when placed at the position E, and illustrates the size that a single lens eyepiece would have to be.

Such a large lens would not be satisfactory, but supposing for the moment that it did exist at the point E, the light would emerge to a position far to the right of E, but remembering the characteristic of the Gauss equivalent lens, it must, having received the light at E, be pushed back to E′ to discharge it, and it emerges to H; and that is the Gauss method of explaining what actually happens in a Huygenian eyepiece.

It will be noticed that neither of the actual lenses employed needs to be of as large a size as the equivalent lens. For if the equivalent lens be placed at E, its position for receiving light, a

lens placed at A need not have as large a diameter to transmit the whole cone, and when the equivalent lens is placed at E′ to discharge the light, a lens placed at B may be quite small, and can be made of deep curvature.

Thus great advantage is obtained by this form of eyepiece by enabling smaller lenses to be used, the upper lens being of considerable curvature and high power, and the total power of the eyepiece is almost as great as that of the upper lens alone.

It also will appear in a later chapter that this form of eyepiece is peculiarly capable of being corrected for aberration errors. The total magnifying power of the eyepiece is dependent upon the focal length of its equivalent lens, and for that purpose the latter

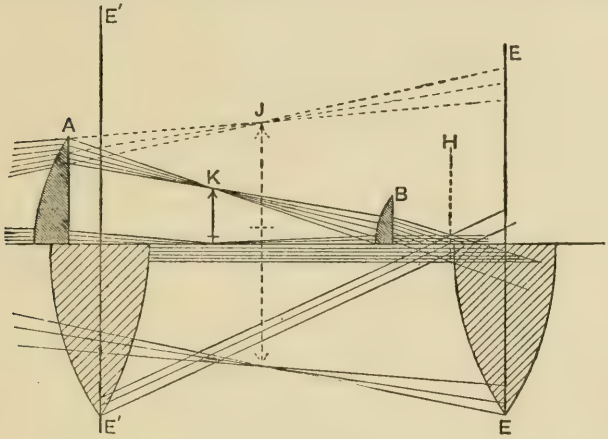


Fig. 23.

may be used as a perfect substitute. The size of the Ramsden circle [1] may be calculated in the usual way by finding the distance of the object-glass equivalent plane from the plane E, and the distance of the Ramsden circle from the plane E′ ; the ratio of their distances will give the relative size of the object-glass aperture to that of the Ramsden circle.

The upper half of the diagram showing the actual path of the rays illustrates that the lower or field lens collects the image that would have been formed by the object-glass at J, before that image is actually produced, and cones it down to a slightly smaller image at K, from which the eye lens B produces a virtual image in the usual manner.

The general optical construction of a compound microscope has now been outlined and Fig. 25 shows the course of the rays throughout the complete system.

The power of a field glass or telescope is often considered as

[1] See Note on next page.

NOTE.—The formula for diameter of the Ramsden circle is obtained as follows. It is a conjugate image made by the eyepiece of the equivalent or nodal plane of the object-glass.

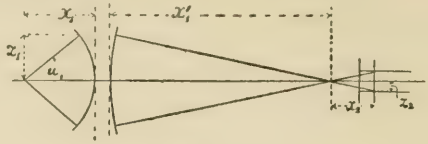


FIG. 24.

z_1 = radius of aperture of object-glass on nodal planes.
z_2 = radius of Ramsden circle.
x_1 = distance of object from object-glass.
x'_1 = distance of first image from object-glass.
n = refractive index to left of object-glass, the refractive index to right being considered 1 (air).
m_1 = magnification of first image.
x_2 = distance of first image from eyepiece.
m_2 = magnification of eyepiece.
ϕ_2 = focal length of eyepiece.

$$-\frac{z_1}{x_1} = \text{Sin } u \qquad n\frac{x'_1}{x_1} = m_1 \qquad x_1 = \frac{x'_1 n}{m_1}$$

$$\therefore z_1 = -\frac{n \sin u\, x'_1}{m_1}$$

$$z_2 = \frac{x_2}{x'_1} z_1$$

$$z_2 = -\frac{x_2\, n \sin u}{m_1}$$

If the light emerges from the eyepiece in parallel beams, $x_2 = -\phi_2$, and

$$\phi_2 = \frac{10 \text{ inches}}{m_2}, \text{ and } m_1 m_2 = \text{total mag. power M.}$$

$$\therefore z_2 = \frac{10\, n \sin u}{\text{M}}$$

If we call $n \sin u = \text{N.A.}$; then

$$z_2 = \frac{10}{\text{M}} \text{ N.A.}$$

The distance of the Ramsden circle from the second equivalent plane of the eyepiece is obtained as follows :—

$$\frac{1}{x'} - \frac{1}{x} = \frac{1}{\phi_2}$$

$$x' = \frac{\phi_2 x}{x + \phi_2}$$

x = distance of second equivalent plane of the object-glass to first equivalent plane of the eyepiece.
x' = distance of Ramsden circle from second equivalent plane of eyepiece.

a whole. If a field glass magnifies 10 diameters, it is left to the decision of the optician as to how much shall be done by the object-glass and how much shall be done by the eyepiece, but a microscope is provided with more than one object-glass, and more than one eyepiece, in order that different magnifying powers may be obtained with the same instrument.

As different combinations can be made, the part played by each portion must be understood by the observer.

The magnifying power of a simple microscope has been considered, it has been shown to be a constant quantity dependent upon its focus. The eyepiece is a simple microscope used to examine the image A′ C′ formed by the object-glass; it forms a virtual image of this at I K; the distance at which this virtual image is formed is always taken to be at 10 inches, therefore

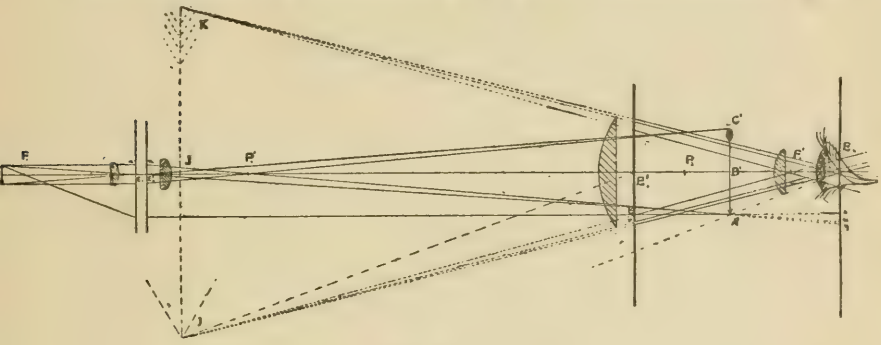


FIG. 25.

10 inches divided by the equivalent focal length of the eyepiece is a measure of its power. The question as to whether the virtual image really does exist at its assumed position of 10 inches from the eye, or whether, due to accommodation, it actually exists at another point, introduces a slight modification, but does not seriously invalidate the fact that a 2-inch eyepiece magnifies five, a 1-inch ten, and so on.

Thus the power of the eyepiece is easily ascertained, and the power of a microscope is best considered in connection with its two component parts, the object-glass and the eyepiece.

The magnifying power of the object-glass is a matter of more complexity. As illustrated in a previous diagram, a lens will produce an actual image of an object with different degrees of enlargement according to the positions of the object and its image with reference to the lens. The magnifying power therefore depends on the equivalent focus of the lens in connection with the tube length of the microscope. If a microscope has a longer tube the image will be formed further away, and the image so formed is larger than if the tube were shorter. It must be

ascertained therefore in expressing the power of an object-glass what is the tube length of the microscope on which it is used. This sounds simple enough. The objection that microscopes are provided with a telescopic tube is no difficulty, because a draw-tube, as it is termed, is graduated. The effect of increasing the power by extending this tube can readily be calculated. That is no doubt true, but the calculation is not quite so easy as might be supposed, and for this reason. A microscope may have a tube length of 140 millimetres, a revolving nosepiece may be added increasing it to say, 150, the draw tube may be pulled out 10 millimetres, making a standard tube length of 160 millimetres (a standard tube length for short microscopes generally adopted); but what relation does the mechanical tube length bear to the magnifying power of the object-glass? The size of the image formed by the object-glass will depend on the position at which it gives an image that will be focussed by the eyepiece. Now the eyepieces have all different focal lengths and drop into the microscope body, so that the point marked Fig. 26 (A), where the image will be formed, will vary with each. The object-glasses are all different lengths, and their back equivalent planes are in different positions with reference to the tube of the microscope. So that the mechanical tube length gives no clue to the optical distance between the eyepiece and object-glass. It might at first sight be considered a bad piece of design.

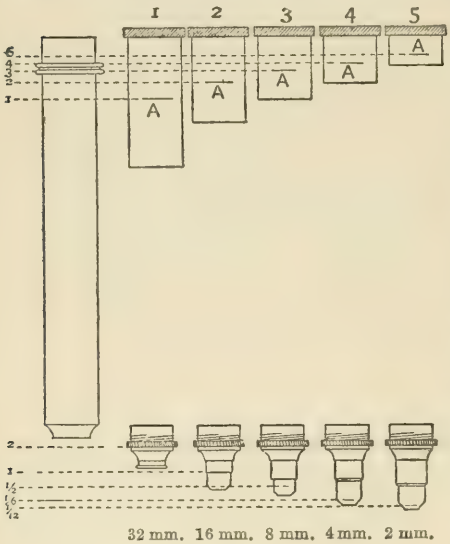


Fig. 26.

The eyepieces could no doubt be made to project from the tube to varying extents so that the positions A should all occupy the same plane, but the microscopist who had just arranged his instrument to the exact height for comfort would object to having another inch and a half added when he wished to change his eyepiece, while it would be impossible to arrange on a binocular microscope, as the distance between the eyes would be changed by a change of eyepieces. As to object-glasses, if their lenses were all to occupy the same position a 2-inch would require a

mount nearly an inch longer than a 1/6th, which could not be tolerated. It is now the general practice to make object-glasses of such a length that when they are swung round on a revolving nosepiece they are approximately in focus. This requires that the lower powers should be shorter and not longer than the higher.

An attempt was made in the early days to get over the difficulty by calling the object-glasses by a focal length which was incorrect: thus an old 4-inch object-glass had actually a focus of about $2\frac{1}{2}$ inches, but gave a magnifying power approximately the same that a 4-inch would have given had it been mounted further from the tube to fulfil the tube-length condition. The system did not work satisfactorily, as it was based on an error, and calculation was rendered by its means even more difficult.

The eyepiece is an instrument that by its nature always gives a constant magnifying power, while the object-glass varies with the tube length employed. A system of making the eyepiece magnification vary with the tube length has been suggested, and to some extent adopted, but this method is wrong in principle, and in consequence leads to serious errors, as soon as the conditions are varied; as, for instance, in projection microscopes and photomicrography.

It is worth noting as a rough guide that a 1-inch object-glass with a 6-inch tube magnifies in the neighbourhood of six diameters, a $\frac{1}{2}$-inch twelve, and so on; with a 10-inch tube, the 1-inch would give about ten and a $\frac{1}{2}$-inch twenty diameters; but for greater precision the table on page 77 of *The Microscope, a Simple Handbook* may be consulted, while for accurate work the magnifying power should be measured as described on page 69 of the same treatise.

We have now seen the broad lines on which a compound microscope is constructed: how great magnifying power, combined with a large field and sufficient working distance, is obtained. In the next chapter the *defects* of lenses, and how they are corrected, will be considered.

CHAPTER II

THE CORRECTION OF LENSES

Errors of single lens—Refraction different for light of different colours—Chromatic error—Achromatic correction—Apochromatic correction—Spherical aberration—Method of correction—Sine condition—Gauss spherical surfaces—Unequal chromatic magnification—Correction—Typical object-glass construction—The Huygenian eyepiece—Its colour correction—Correction for spherical aberration.

It has been shown how a lens produces an image of an object; also how by suitable arrangements of lenses an efficient method has been developed of producing a highly-magnified image of an object. This chapter will be devoted to the consideration of the optical quality of such an image. An efficient microscope must not only produce a magnified image of an object, but that image must be a clear and well-defined picture, otherwise it will probably not reveal any structure that could not be seen by the naked eye. Even a cursory examination of the image produced by a simple uncorrected lens demonstrates that the picture which it forms is far from perfect. It has fuzzy outlines and coloured fringes, and that portion which is formed by the light which passes through the lens in an oblique direction shows still more serious defects.

The scope of this book does not permit of a complete explanation of all the corrections of lenses, but the chief errors that are met with in designing a microscope and the methods by which they are corrected will be discussed.

The most satisfactory method of considering an optical image is to first examine the picture which is formed by the lens of a single minute point of light. Every object consists of a mass of points in juxtaposition, and an apparatus that is capable of producing a point image of a point source of light placed in succession in the various positions occupied by the object will produce a well-defined and clear picture of that object.

Fig. 27.

If a point of light is depicted by a lens as a fuzzy disc, a line which consists of a row of points will be depicted as a series of

fuzzy discs overlapping each other (Fig. 27), and the outline of an object will appear indistinct and hazy.

Microscope lenses must be unusually perfect in their image-forming qualities, because the images which they produce are highly magnified, and any imperfections will also be highly magnified.

No matter how well constructed a single lens may be, it possesses numerous defects—defects which are due to different causes and are remedied by different means—and it is well to treat them separately. We will commence with the chromatic error, and then consider the chief spherical aberrations; proceeding to discuss later some of the less obvious, but equally important defects.

Until the early part of the nineteenth century no means was known of correcting the defects of a single lens, and the microscope was restricted in consequence to the use of comparatively low magnifying powers.

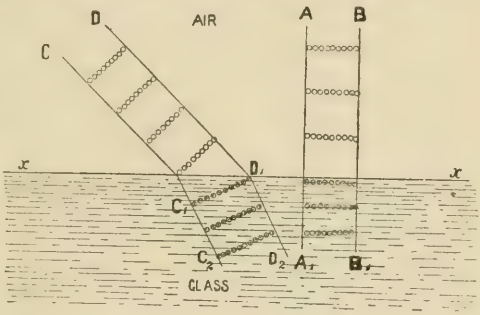


FIG. 28.

The properties of a lens depend upon the fact that it is made of a dense material, such as glass, which retards the rate of speed at which light travels as it passes through it. A beam of light, A B A_1 B_1 (Fig. 28), striking a glass plate at right angles to its surface, passes into the glass; it is reduced in its speed of travel but it is not altered in its direction. If it strikes the surface obliquely as at C D, the portion C strikes the glass first and is retarded while the portion D is travelling at its full speed, so that the portion C has only reached C_1 by the time the portion D has reached D_1 on the surface of the glass. After this the two portions travel at the reduced rate of speed, but the direction has been altered at the surface of the glass and the light is said to be refracted or bent.

Light is a vibration, and may be considered to be a movement of particles of a hypothetical material called ether, just as sound is a vibration of particles of air; but white light is not a single vibration, similar to a single musical note, but a complete octave of notes travelling together. If it be dissected into its various components or individual notes it is found to consist of a series of vibrations, each of which has a different period, and each of which produces upon the eye the effect of a different colour.

The reason why glass retards the motion of light, is that vibrations cannot take place so easily in the denser material, and the different colours, each vibrating at a different rate, are not affected to the same extent, and thus glass retards the short wave-length colours, such as violet and blue, to a greater extent than the longer red and yellow vibrations, and the violet and blue light is bent or refracted to a greater extent. A beam of white light refracted or bent by a prism shows for this reason a coloured spectrum, because the light of each colour being refracted to a different extent occupies a different position after it has passed through the prism.

The well-known colours of the rainbow or a spectrum of primary colours seen in a spectroscope—red, orange, yellow, green, blue, violet—are produced in this manner by splitting up white light into its component colours.

A lens, when it bends the light which passes through it, acts in the same way as a prism upon the different colours. Suppose A, Fig. 29, to be a point radiating light in all directions, all the light that can pass through it to the further side of the lens C C_1 is included in the cone A C C_1, and in order to produce a perfect picture of a point, A, by means of a lens, it is necessary that every one of the rays of light which emerges from A shall pass through a point B.

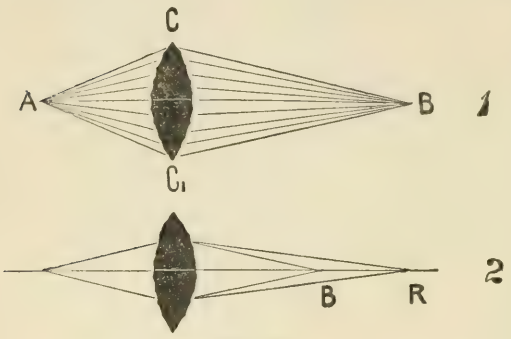


Fig. 29.

If the shape of the lens be such that every portion of its surface is arranged in little facets, each facet being so placed as to bend the ray of light which strikes it in the correct manner, this could be achieved for one-coloured light; but as different-coloured light is refracted differently it cannot be done with any single lens for all colours, and the blue light will be refracted to a point at B, Fig. 29 (2) while the red is focussed to a point at R; thus the focal length or refracting power of a lens is different for different-coloured light. A screen placed at R will show a red centre surrounded by blue-coloured edges, a screen placed at B will show a blue centre surrounded with red edges.

This chromatic defect possessed by a simple lens is called chromatic aberration, and its correction is called achromatism.

Achromatic correction is possible, because the optical pro-

perties of glass can be varied according to the materials used in its manufacture. Two kinds of glass can be made, one of which has a greater effect on different-coloured rays—what is called greater dispersion—than the other, but has the same average refraction.

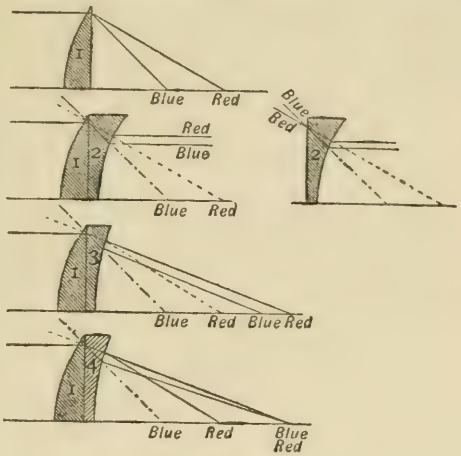


Fig. 30.

Suppose two lenses (Fig. 30), 1 and 2, which are of the same focus, are composed of the same kind of glass, it is evident that the errors of 1 exactly neutralise the errors of the other, 2, because 1 is positive and 2 is negative, and one is the exact converse of the other, but the lens 1 neutralises the lens 2 in every other way, and a plane piece of glass having no lenticular qualities is produced. If a negative lens be made of a lower power, as at 3, a partial neutralisation of the colour error takes place, but only to the same extent as the neutralisation of the lenticular action, and thus no correction is obtained: the lens might just as well be of solid glass. If, however, the negative lens, as at 4, is made of a glass which has greater effect on the blue rays than lens 3, and the same effect on the red rays, then a combination can be obtained to correct the colour error.

If, as shown in Fig. 31, two lenses, A and B, are of the same focus and made of the same glass, they neutralise each other, both as to their errors and every other characteristic, but if the negative lens, C, is made of a glass that has double the dispersion or effect upon the colour, it needs only half the power to correct the colour error, and the lens, A, is only partially neutralised by C, the combined pair still having the properties of a lens, although reduced in power. Therefore, to correct the central colour aberrations of a thin positive single

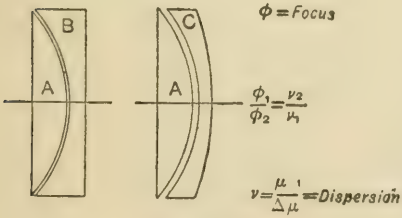


Fig. 31.

lens, all that is required is to combine with it a negative lens of greater dispersion, making their foci in the exact ratio of the dispersion of the glasses of which they are made.

$$\frac{\phi_1}{\phi_2} = \frac{\nu_2}{\nu_1} \qquad \phi = \text{Focal length.}$$
$$\nu = \frac{\mu}{\Delta\mu} = \text{Dispersion.}$$

This simple formula for the correction of achromatism is easily remembered, and it should be particularly noted that it only involves that the focal lengths of the two lenses of the combined pair should be in a definite ratio, and does not put any further limit to the shapes or curves of the lenses. It only applies in this simple form to thin lenses in contact, and it is a somewhat more complex formula when thick lenses are used, or when the lenses are placed at a considerable distance apart. It has a further limitation due to another property of glass, which may be illustrated by a diagram (Fig. 32). Suppose the colour aberration of a single positive lens be illustrated by the height of the line, A B for one colour, C D for another colour, and E F for a third, and suppose the aberration of a similar focus negative lens, with double the dispersion, is represented by the diagram to the right of this, when the two diagrams are superimposed as shown to the extreme right, they extinguish the aberration; but this is because the action of the glass has been in both cases regular and has affected every colour relatively to the same extent. Unfortunately the action of glass is irregular and is more nearly represented by the curved lines of the lower diagram, and when the two lower diagrams are superimposed it will be observed that at no position can the aberration be entirely cured. Any two points can be exactly corrected, but a small residuum of colour called the secondary spectrum is left. Lenses corrected in this manner are called achromatic.

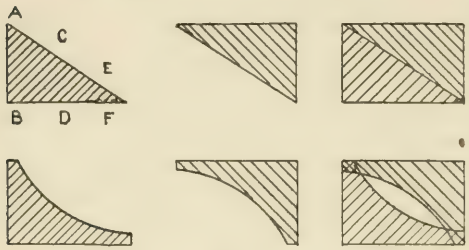


FIG. 32.

With certain special kinds of glass in combination with fluor spar, three colours instead of two can be exactly corrected, and the amount of colour then visible in an image formed by them is so small as to be negligible.

Lenses corrected in this way are called apochromatic; the advantage of microscope apochromatic lenses would, however, be very slight if they possessed no other quality than this slightly

improved colour correction. The correction of their other errors can be greatly improved, with the result that unless the very highest-power eyepieces are used it is difficult to recognise any errors at all. The slight residuum of the secondary spectrum is not of sufficient intensity compared with the whole quantity of light to impair seriously the quality of the picture except for special purposes.

The next error in a simple lens, called spherical aberration, is a consequence of the practical fact that spherical curves are the only surfaces that can be accurately ground on lenses. The cup-and-ball motion is the only known method of grinding and polishing a true optical surface. This motion enables the whole of a surface to be ground evenly. Any other surface, as, for instance, a parabolic surface, cannot be ground; the process of grinding would take place irregularly because unless the rubbing and grinding action can take place in more than one direction, the surface will be ground unevenly at different parts, and it is evident that two parabolic surfaces cannot be moved upon one another while remaining in contact except by revolution on one axis. Thus all lenses, if they are to have perfect surfaces, must be spherical in shape.

Referring back to Fig. 29, we notice that a lens with surfaces that consist of a series of minute facets will accurately focus light from a point, so that it is refracted to another point, and if we make these facets sufficiently small and sufficiently numerous the surfaces become curves; but unfortunately these curves do not prove to be spherical surfaces.

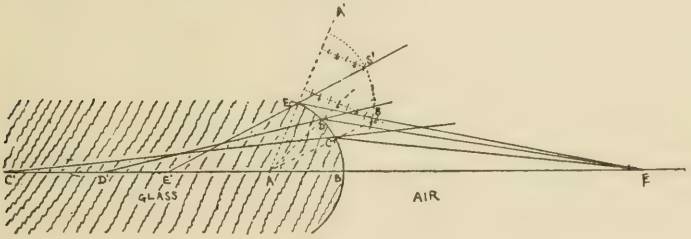


FIG. 33.

Fig. 33 illustrates the defect of a spherical surface. The refraction of light follows a definite law, expressed by the equation $\frac{\sin i}{\sin r} = \mu$, namely that the sine of the angle of incidence is in a constant ratio to the sine of the angle of refraction. This constant depends on the nature of the glass employed, and is called the refractive index of that glass.

A spherical surface with a centre A is represented by the line B C D E, and a ray of light is incident on the surface from a point

F on the axis. The diagram shows the direction of the rays after refraction at a spherical surface, thus the lines E E′, D D′, C C′ correctly represent the refracted rays which correspond to the incident rays F E, F D, F C, etc. The light which passes through the surface at a position close to the axis at C comes to a focus at C′; that which passes through further away at D comes to a different focus at D′; while further away still it focusses at E′, showing that the whole of the light coming from a point is not brought to a focus at another point, and there is no position where a sharp image can be obtained. If a screen be placed at any position between E′ and C′, the point object will be represented by a fuzzy disc of light instead of a point. This error is not very marked in light at a small angle from the axis, but rapidly increases as a large angle of light from the object is refracted by the surface. It will be seen subsequently that one of the essential requirements of a high-power microscope object-glass is that it should collect a very large angle of light from every point of the object, and consequently the correction of this error is a matter requiring more attention than any other in microscope construction.

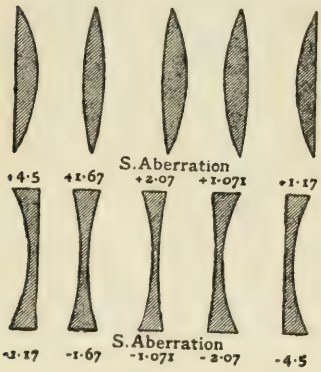


FIG. 34.

If two spherical surfaces be used, thus forming a lens, this defect will exist at each surface. In certain shapes of lenses the two surfaces acting in the same manner exaggerate the defect. In other shapes they balance each other to some extent, but no single lens of two surfaces can be made even approximately free from the defect with any known refracting medium.

Thus the shape of a lens has a great effect on the amount of spherical aberration. The diagram (Fig. 34) shows a series of lenses all of the same focus, but of different shapes, and having consequently very different amounts of spherical aberration. The same method of correction may be adopted as in achromatism, of making a powerful positive lens and partially neutralising it with a negative lens, which, although it has a lower power, has greater relative aberration, due to its different shape, and which thus neutralises the error of the more powerful positive lens.

The method of correcting achromatism is by making the foci of a positive and negative lens in a certain definite ratio, but the lenses may be of any shape. The method of correcting spherical aberration is by making the shapes of the lenses of suitable form, thus it is possible simultaneously to correct these two errors, the colour correction being in no way antagonistic to the correction

of the spherical aberration. But as with achromatism so with spherical aberration, complete correction is only obtained with very great difficulty.

When the central rays are brought to the same point on the axis as those of the edge it does not at all follow that the intermediate zone of the lens is also focussing the light to that point (Fig. 35); a residual so-called zonal aberration remains, which, in the case of the microscope, is one of the most serious difficulties to be overcome, because the aperture of a microscope object-glass is so large compared with its short focus. The full correction is obtained by using more than two lenses with suitable shapes, five, six, and even ten lenses being sometimes required, but the entire correction of the spherical aberration error, being a question of elaborate arrangement of the shapes and distances apart, cannot be followed in detail.

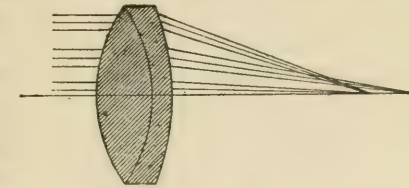


Fig. 35.

The means of correcting a lens system so that all light coming from one point on the axis shall be refracted to another exact point on the axis has been now considered. Let us suppose that by the methods explained we have eliminated the central colour aberration and the central spherical aberration from a lens combination. It might be expected that for small areas close to the axis such a lens system would produce reasonably perfect images. This is, however, by no means necessarily the case, and the next diagram (Fig. 36) will illustrate the way in which a lens system may give a perfect image of a point which is exactly upon the axis, but a very bad image of a point which is even to the slightest extent away from the axis.

Suppose that a lens that is corrected for central spherical aberration is split up into several portions, A, B, C, D, one for each zone of the lens, and that each portion is represented by a separate small lens, it is evident that there are many ways of so compounding a series of small lenses that all the light from X will arrive at X′. Fig. 36 (1) shows a method in which all the lenses are above one another. Fig. 36 (2) shows a method in which the lens D is some way to the right of lens A. Both these arrangements may be made to give a perfect correction for central spherical aberration, but it is evident that in the arrangement in Fig. 36 (1) the lens D must have a longer focus than the lens A, as the distance D X is longer than the distance A X but to only a slight extent, whilst in the second arrangement the lens D must be of much longer focus than the lens A. The central spherical aberration is corrected in both these figures, but by

different methods, and we should not expect to find exactly the same results produced. The difference in the two methods will be evident when we remember that the size of an image formed by a lens depends upon its focal power, and therefore in Fig. 36 (2) the image of the object formed by the lens D will be much smaller than the image formed by the lens A, in fact, almost half

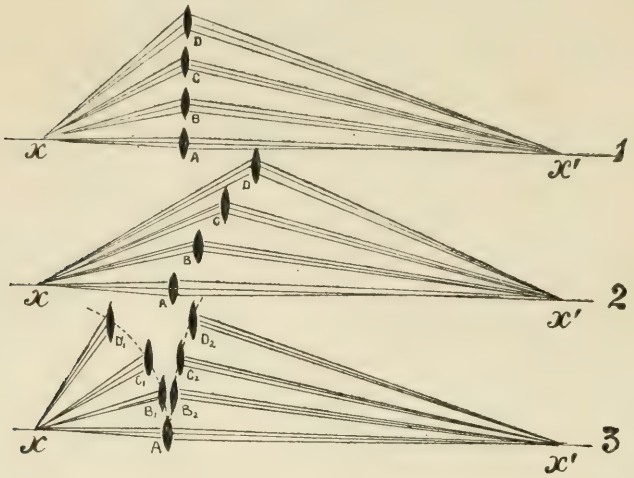


Fig. 36.

the size. The effect of this will be confusion in the picture, a number of images of different sizes overlapping one another. The exact point in the centre may be correct, but the slightest fraction away from the axis and all is fuzzy and indistinct. There is not even a small area where a good image will be formed, but only one exact point. The case illustrated in Fig. 36 (1) is much better in this respect, because the lens D is not much longer in focus than the lens A, but the defect exists even there.

To produce even a small image of good quality, each of the lenses, A, B, C, D, must have the same focal length, so that each will give the same size image, and if this is so, each lens must be placed at the same distance from X, as shown at Fig. 36 (3), so that the distances, A X, B_1 X, C_1 X, D_1 X, are all equal; in fact, the refraction must all take place as from a circular line, with its centre at X; but it will be observed that for this purpose to be attained the lenses should also be placed at A, B_2, C_2, D_2 Fig. 36 (3), on a circle, with the point X′ as its centre, in order that they may also be at equal distances from the image X′, because, as seen in the first chapter, the relative size of object and image depends on their relative distances from the lens. Suppose an optical system of lenses to be made which has the properties

which satisfy the Gauss plane condition, in which the light behaved as though at the point D_1 (Fig. 36, 3), there was an equivalent lens to receive the light, which jumped to D_2 to discharge it, and suppose at C_1 and B_1 the light behaved as though the equivalent lens jumped to the positions C_2 and B_2. This optical system would fulfil the condition that is required to give perfect image formation for a small area in the centre of the picture, namely, all the rays would form images of the same size. In fact, to make a perfect image-forming apparatus of this nature, the equivalent planes of Gauss must be made spherical surfaces, with the object and image as their centres. It will be observed that a property possessed by rays of light which are refracted by such a system is that the sines of their incident and refracted angles with the axis are equal to a constant quantity, and that constant quantity is the magnifying power of the system, because it represents the relative distances of objects and image $\frac{\sin i}{\sin e} = \frac{A\,X}{A\,X'}$. Thus this condition which has to be complied with in order to form a perfect image at the centre of the picture is generally called the "sine condition." This condition was first proved theoretically by Helmholtz, by photometry, and by Abbe, by Fermat's least time principle (it is demonstrated here by a simple geometrical proof), but before this, Frauenhofer had shown the necessity of it for constructing telescope object-glasses, and Lister had shown, in 1830, the means of arriving at this important correction in the manufacture of microscope object-glasses. The defect which arises when it is not corrected he called "coma," a term which, strictly speaking, describes the defect, although it is now more generally applied to a similar defect at the edge of the picture. For twenty years after the date when Lister, improving upon the purely haphazard methods of Chevalier and Amici, had shown how aplanatic microscope object-glasses could be made, the Lister formula lenses were considered the best in the world, and this was due to the fact that by the elimination of the comet-form tails known by the name of coma, which existed in images of points of light which were pictured near to, but not absolutely in the centre of, the field, the so-called sine condition was satisfied. Too little attention has been given by recent writers to the work of Lister. He discovered the two pairs of spherically correct conjugate foci of a lens, one of which was over- and the other under-corrected for the sine condition, and showed how, by making use of the over-corrected focus of one lens with the under-corrected focus of the second lens, coma could be eliminated.

This explains the third important correction that has to be made in microscope object-glasses, namely, the sine condition. If a large picture is required, if, for instance, a photograph is to be taken to include a view that subtends, say, 60°, it can be shown

that the optical instrument, to project such a picture without distortion and with good definition at the edge of the field, must be made so that it fulfils the condition of the Gauss equivalent planes, and that those planes must be flat and not spherical surfaces. In this case the angles of the incident and their refracted rays with the axis are in the ratios of their tangents, and not of their sines. Thus it would appear that if a picture is to be absolutely sharp in the centre, it will not be absolutely sharp and free from distortion at the edges, and this is the case ; but the difference between the sine and the tangent is a negligible quantity for small angles, and, therefore, if moderate cones of light from each point of the object are used, the two conditions can be simultaneously satisfied. In the case of photographic lenses, the half-cones of light received from each point of the object being seldom more than 5° or 6°, the straight-line Gauss planes can be assumed to exist. High-power microscope lenses, however, often admit cones with a semi-aperture of 75°, and the sine condition must be satisfied in order that perfect central definition may be obtained. The great magnifying power makes the absolute perfection of the image a necessity, consequently the definition at the extreme edge of the field of a high-power object-glass is somewhat sacrificed for the benefit of central definition. It is, however, interesting to observe that when the tangent condition of the flat equivalent planes is satisfied, instead of the sine condition with the spherical equivalent planes, the result in the centre of the field is not far from correct, and is far superior to that which is frequently obtained with lenses which, though corrected for central spherical aberration, are not corrected for either the sine or tangent condition.

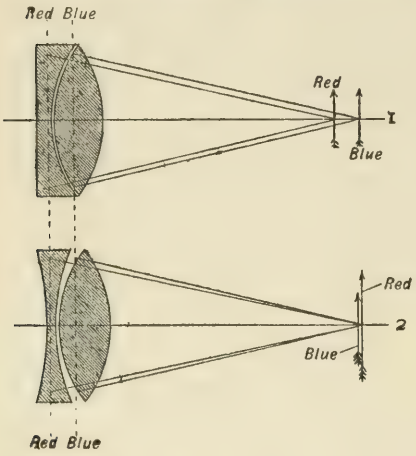


FIG. 37.

The colour correction must also be investigated from this same point of view. The method of making a corrected lens in such a way that different-coloured light from a point on the axis will converge to another point has been explained, but will the sizes of the different-coloured pictures formed by such a lens be equal and therefore be exactly superimposed, or will they be different and overlapped ? because, if the latter is the case, the

same error will exist that, except for the exact centre, there will be coloured fringes which spoil the definition of the picture. Fig. 37 (1) shows a pair of lenses whose focal lengths are in the same ratio as the dispersion of the two glasses, and consequently all coloured light has the same focal length. It is corrected in the manner previously described, but the equivalent planes for different-coloured light are not in the same position and, therefore, although all coloured light has the same focal length, it does not meet at one point on the axis. In Fig. 37 (2) the foci of the lenses have been slightly changed, so that all the light meets at a point on the axis; but in this case the focal length of different colours is different, and the sizes of the different-coloured images will not be the same. It is therefore evident that for good colour correction something more than equality in focal length is necessary; the position of the different equivalent planes must also be the same. In the last chapter it was described how the position of the equivalent planes was influenced by the shapes of the lenses, and thus, in order to make a perfect colour correction, the lenses, in addition to having their foci in the correct ratio according to the dispersion of the glass, must also have particular shapes so that the equivalent planes of the compound lens may be the same for all colours.

Space will not allow of the consideration of some of the minor points, and the question of optical corrections has only been outlined in the foregoing remarks; but the principal errors, and their method of correction, may be summarised:—

1. Equal Chromatic Focal Length. Correction—Ratio of foci of component lenses.

2. Identical Position of Chromatic Gauss planes or surfaces. Correction—Shapes of component lenses.

3. Central Spherical Aberration. Correction—Shapes of component lenses and their distances apart.

4. Spherical Gauss Surfaces, sine condition. Correction—Shapes of component lenses and their distances apart.

5. Zonal Aberration. Correction—Shapes of component lenses and their distances apart.

If there were only one method of correcting each of these errors, it would be impossible to correct all at one time, but as there are several methods of correcting each defect, the problem of correcting them all in one system of lenses is rendered possible. The correction No. 1 for equal chromatic focal lengths is the one that has the fewest methods of solving, as it has been seen that the satisfaction of this condition immediately fixes the relative focal lengths of the component lenses. This, however, is not quite as fixed a matter as has been stated, because the thickness of the lenses and their distances apart have considerable influence, and a second method of solving the problem can be found when thick lenses at different distances are used; thus there are two

methods of making this correction. The other four corrections are all dependent on the shapes of the lenses, whilst their foci, or their foci thickness and separation combined, are kept at the correct ratio for satisfying the condition No. 1. The number of methods of making these corrections is quite unlimited, depending upon the number of lenses employed to make the complete object-glass. The larger the number of lenses the greater is the possibility of making different combinations of correct shapes; thus, for the correction of each defect that method may be selected which is not antagonistic to the correction of all the other errors. It is advisable to make the lenses as few as possible, because each extra lens introduces chances of error in manufacture and stops light by absorption and reflection. It is evident that the corrections require to be more perfect as soon as high magnifying

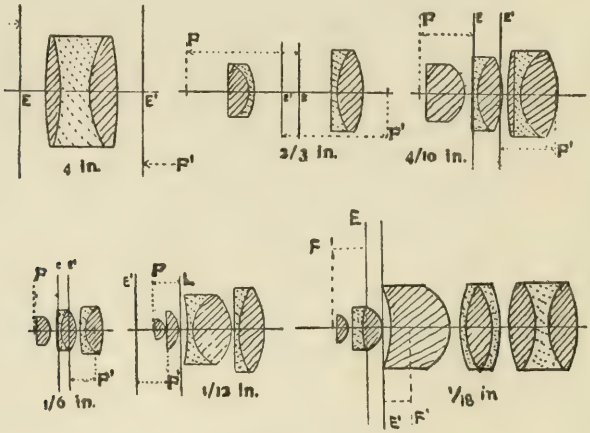


Fig. 38.

power is used, and are much more difficult when large-angle bundles of light are admitted from each point of the object. It will be shown in the next chapter that it is necessary with high magnifying power to admit wide-angle pencils of light, and thus although low-power lenses can be made with a few components, high-power lenses must be constructed of a number. The diagram, Fig. 38, displays a typical series of object-glasses, ranging from a 4-inch to 1/18-inch, the low powers having from three to four lenses while the higher powers have from six to ten components. The best achromatic 1/12 oil immersion object-glasses of about 1·3 N.A. have generally six lenses, and that is the smallest number with which a perfect object-glass with so large an angle has at present been made. The modern microscope object-glass has reached a technical perfection that would be difficult to surpass. The image produced by the object-glass of the microscope

leaves little to be desired except as regards the highest-power lenses, where slight improvements may be hoped for.

It is now well to examine the eyepiece, for when the object-glass is corrected so that the main image is perfect, no deterioration must take place due to the eyepiece that enlarges this image. The eyepiece most frequently employed in the modern microscope is the Huygenian eyepiece, consisting of two plano-convex lenses separated by a considerable interval. Its advantage in giving a large field of view in connection with moderate-sized lenses was discussed in the last chapter, but it has a further very interesting feature, as it shows a different method of making corrections for aberrations. This eyepiece is practically free

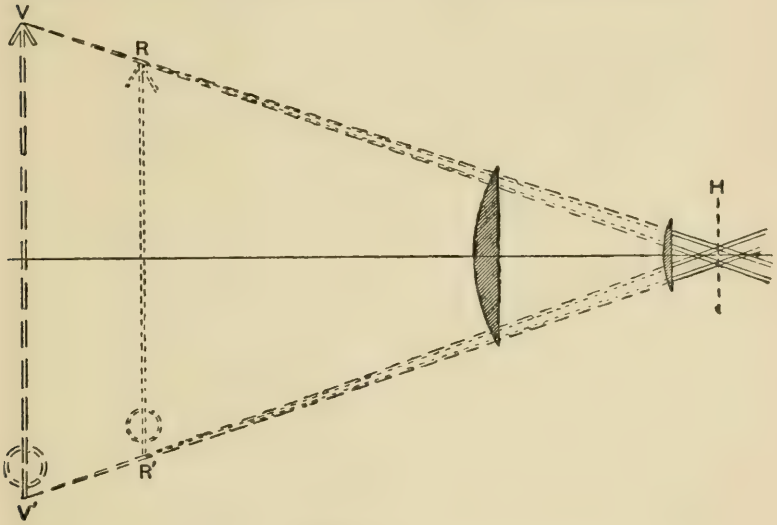


Fig. 39.

from central colour aberrations when used in connection with an object-glass. The usual method of correcting a lens for colour has been explained as requiring a negative lens that has great influence on colour combined with a positive lens which has small influence on colour, so that the negative lens, while entirely neutralising the colour error, only partially neutralises the refracting power of the positive lens. The Huygenian eyepiece, however, consists of two uncorrected positive lenses, both of which are made of glass which has the same influence on colour. The correction is curious, and to understand it thoroughly we must remember that there are two chromatic corrections.

1. Equal focal lengths for different colours, so that the sizes of the coloured pictures may be the same.

2. Equality of position of the Gauss equivalent planes re-

ferring to different coloured light, so that the position of the images may be at the same point.

If, as with an object-glass, an actual image is formed in space, both these errors must be corrected, but with an eyepiece which gives a virtual image the latter condition need not be considered, as will be seen from Fig. 39. The violet image may exist at V V′, and the red image may exist at R R′, two totally different positions, and yet if both these images lie anywhere along the lines H V and H V′, their pictures will be superimposed, and no indistinctness will be caused by their being situated at different positions. They will be the same angular size, and will lie on the lines H V and H V′, provided the total eyepiece has equal focal lengths for different colours. Therefore, the first condition of equal focal lengths only need be satisfied.

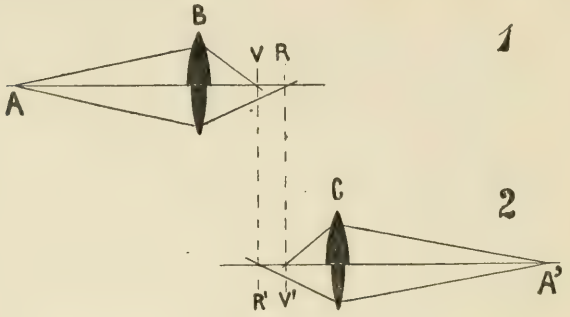


FIG. 40.

It is evident from a diagram that a pair of uncorrected positive lenses could not produce the different-coloured images at the same point. The lens B (Fig. 40) will produce a picture of the point A, by means of the red rays at R, and by means of the violet rays at V, closer to it.[1]

Now, consider a second lens, C, forming a perfect image at A′; in order to do this, the upper half, representing the violet light, is, as before, a more powerful lens than the lower half, and the violet image, if it is to focus to A′, must start from V′, and the red from R′, the very reverse positions to those in which they actually exist after having passed through the first lens. Thus a pair of positive lenses will not produce the images in the same position, and it has been shown that with a virtual image as seen in the microscope, this is not necessary. How then can the chromatic focal lengths be the same, if the positions of the foci themselves are different? Focal length is a measurement of a

[1] To illustrate the fact that a lens produces a greater effect on the violet than the red light, it is drawn as a more powerfully curved lens in the upper half of the diagram than in the lower.

distance, the distance from the focus to the equivalent plane. If the different-coloured foci, which are the points at one end of this distance, are different, the different-coloured equivalent planes, which are at the other end, must be different to a similar extent, and the focal lengths can then be the same.

That is exactly what happens in a Huygenian eyepiece. Ev (Fig. 41) is the position of the second equivalent plane for violet light, Fv is the focus, Er is the red equivalent plane, Fr the focus, and the violet focal length, F′v, E′v, is equal to the red focal length, F′r, E′r.

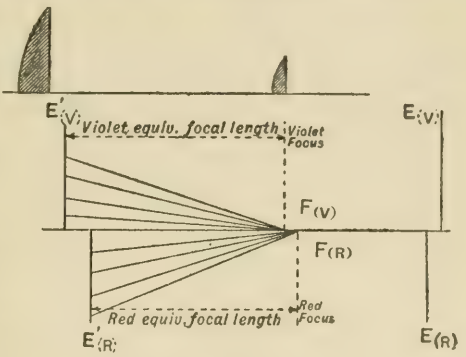


Fig. 41.

There is an advantage in this kind of correction when used in combination with a microscope object-glass, in that it allows of two different methods of making a perfect microscope. The object-glass may be absolutely corrected in itself and throw a perfect image into the eyepiece. The eyepiece then produces the different-coloured images of exactly the same size, but at slightly different positions, which are, however, as described,

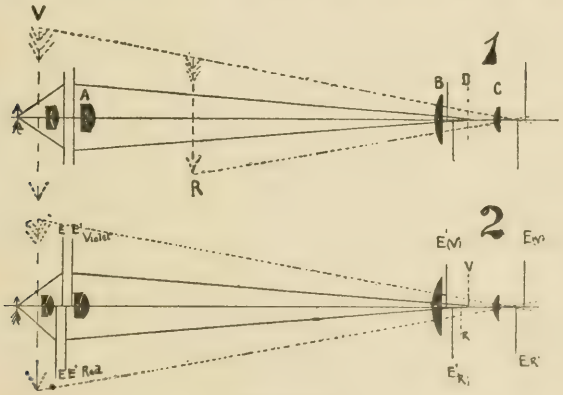


Fig. 42.

superimposed in the eye, or the object-glass may be made so that it gives its different-coloured images of the same size, but at slightly different positions, which error is corrected by the eye-

piece. Fig. 42 (1) shows the first method when the object-glass has its focal lengths equal for different colours, and also its equivalent planes, and a perfect and superimposed image is thrown into the eyepiece at D, the eyepiece B D then produces virtual images, R and V, which are in different positions, but these, however, are superimposed in the eye. Fig. 42 (2) shows an object-glass which has equal focal lengths for different colours, but in which the equivalent planes are not in the same position, and thus the violet image is thrown into the eyepiece at V and the red at R, just the positions which are required to enable the final images to be produced at the same place. It will be seen that this error of position in the equivalent planes of the object-glass is of the nature of an uncorrected lens, the violet plane being to the right of the red, and thus the task of correcting

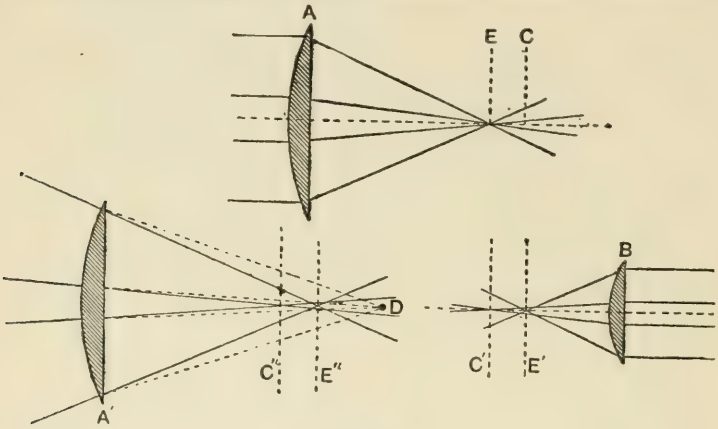


Fig. 43.

an object-glass is rendered somewhat easier. As a matter of practice, a compromise is the usual method employed and an object-glass is generally slightly out of correction. It may here be emphasised that the data given in ordinary textbooks should not be used as a basis for accurate investigations of eyepieces. The Huygenian eyepiece is there given as having lenses with focal lengths of 3 to 1, with a separation of 2. The eyepieces by one of the largest English microscope makers are more nearly 2 to 1, with a separation of 1·6. The error of spherical aberration is also corrected in a Huygenian eyepiece, but in explaining the principle the Gauss equivalent planes cannot be used. They do not apply to anything but the central rays, except in the corrected system. The exact explanation is best displayed by mathematical formulæ, but the method can be illustrated (Fig. 43). Suppose parallel light to be entering the lens A the edge rays will be focussed to E, nearer to the lens than the central rays

which focus to C. Now consider a second lens, B : in order to emit a parallel beam the edge rays must enter from E′, and the central rays from C′, which is the reverse of the position in which they are placed by the first lens A, thus for parallel rays this system would not be corrected, but would be worse than a single lens ; but if the light is coming into the lens A′ converging to a point D, which is the case in the microscope, a reverse aberration takes place and the central rays go to C″, nearer the lens than the edge rays which meet at E″.

It is evident that under these conditions the lenses A′ and B combined together will neutralise the aberration if they are constructed in the right proportions. The intermediate image produced by the lens A′ is incorrect and fuzzy to exactly the extent that the image would be if formed by the lens B with the light going through it in an opposite direction, and thus acting together a perfect image is formed.

The corrections of the rays which pass obliquely through a lens have in the case of the object-glass been disregarded, because the field of view of the object-glass is small ; it is evident that in the eyepiece this is not the case and they cannot be disregarded. The description of the Huygenian eyepiece is sufficient to indicate the general requirements of an eyepiece. It is the cheapest and most usual form. It is not as good as the compensating eyepiece, it has not so large a field as the orthoscopic type. There are many forms of eyepieces with special characteristics and their complete optical description is beyond the scope of the present book.

CHAPTER III

APERTURE AND RESOLUTION

Straight-line propagation of light—Modified by diffraction—Diffraction at a slit—At a circular aperture—Diffraction pattern of a point object—Anti-point—Aperture of telescope—Aperture of microscope—Resolution due to aperture—Numerical aperture—Table of aperture and resolution—Anti-points due to apertures of different shapes—Resolving power and magnifying power—Spurious resolution—Conditions for best resolution.

In order to understand image formation by a microscope, the way in which light travels must be considered in a more exact manner than is required in an ordinary study of the formation of images.

The general explanation of the formation of images by a lens is based on the assumption that light travels in straight lines. The direction of the light is altered by a lens, each of the straight-line rays being bent at the surfaces, but after each bend the light again travels in straight lines.

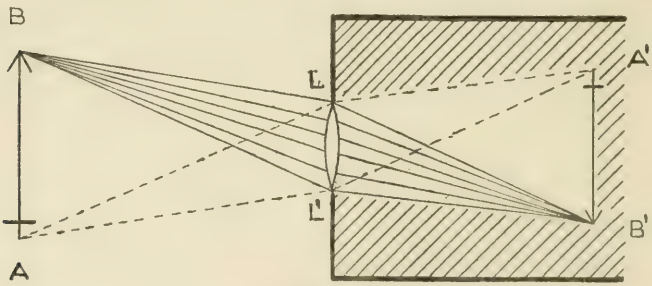


Fig. 44.

Thus if A B (Fig. 44) represents an object, and L L′ a lens set in the side of a dark box, the various straight lines from a point B, which are included in the cone L B L′, represent all the light that can enter the box from the point B; and if the lens L L′ has the power of bending or altering the direction of all these straight lines so that they meet at a point B′ on the interior surface of the box, an image of the point B will be produced at the point B′. Every point in the object A B will send out rays, and these rays will be brought to corresponding points in the space A′ B′, an image which is a representation of the object

being formed at the back of the box. On this simple view the whole of the light which enters the box from the object A B is supposed to play its part in forming the image A′ B′.

As a general statement this is true. As a general statement it is also true that all river-water flows into the sea, but a closer examination may show that some of the water evaporates and some is absorbed along the banks, where it irrigates the land.

Such general statements prove on close examination to be not strictly accurate, and the cone of light from B does not all arrive at an exact point B′ even with a perfect lens. The majority of the light will arrive at the point B′, just as the majority of the water in the river will enter the sea, but a small amount is distributed around the geometrical image B′. It is comparatively small and is not detected unless the resultant image is critically investigated. In using a microscope, however, the image itself is much larger than the original object, and in examining the image it is again magnified by means of the eyepiece. The purpose of the microscope is to examine the object with great accuracy in order to reveal otherwise hidden structure, and any factor that even slightly damages the perfection of the image must be considered. This renders it necessary to investigate carefully the scattered light which does not travel according to the general law of geometrical optics.

If an opaque object be placed between a candle and the observer's eye, most of the light does not go round the obstacle; the candle is obscured and the scattered light which reaches the eye after bending round the obstacle is too feeble to be noticed. If in the course of the travel of a ray of light, A B, Fig. 45, the action of a particle, say at C, is considered; when the ray from A first strikes it, this particle is caused to vibrate up and down and it has no greater tendency to communicate its motion in one direction than another. The propagation of light waves resembles that of the movement of the ripples formed on the surface of water; when a stone is dropped into water it communicates the disturbance in all directions, as shown by a system of circular waves (Fig. 46 B), which travel outward from the point of impact, but a row of adjacent stones dropped simultaneously into the water will not form a series of circles arising from each stone. The wave created by one stone has a certain influence on that of its neighbour, and the result is that as far as the central portion of the row of stones is concerned, a straight wave travels outwards and the vibration proceeds in a straight-line direction (Fig. 46 A). Such also is the case with light; a body of light travels in straight lines, not from any quality of its own, but because each individual ray or disturbance, although it has a tendency to wander in all directions, is kept in a straight course

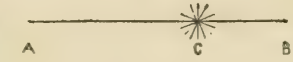


Fig. 45.

by the influence of the rays (or disturbances) adjacent to it. Referring back to the wave system set up by a row of stones, it will be seen that at the ends of the row the wave disturbance travels outwards in all directions. A similar effect takes place when we consider a beam of light the breadth of which is limited by passing through some form of aperture. The central portion travels along in straight lines, but from the sides of the beam, rays (or disturbances) travel outwards in all directions.

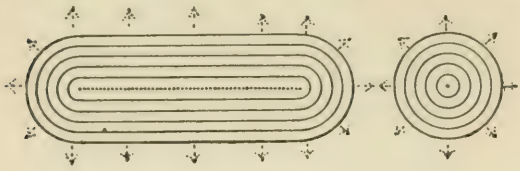


FIG. 46.

The spreading of light from the sides of the beam is called "diffraction," and the light which does not travel in the direction of propagation is called diffracted light. The intensity of the diffracted light is only a small percentage of the total if the beam is of considerable width, and it only becomes a large proportion if the beam is very narrow.

The statement that light travels in straight lines and the conception of diffraction as a supplementary phenomenon is a useful but inaccurate method of expressing the case. The facts are more truly stated by saying that light travels in all directions, but that when a sufficient body of light is considered it travels mainly in only one, because each individual ray is so controlled by its neighbour that all the light except that at the margin moves in one direction. The diffraction of light explains why the edges of a shadow, even under the most favourable conditions, are not perfectly sharp; there is always a fuzzy outline caused by the diffracted light which spreads into the penumbra. An X-ray photograph of, for instance, the bones of the hand is nothing more than a shadow made by X-ray light, and to those who have tried to photograph the shadows formed by ordinary light, the brilliancy of the definition of the X-ray photograph when taken with a suitable X-ray tube is surprising; it is because the X-rays have no perceptible diffraction and, therefore, a perfectly clear and defined shadow is produced.

A remarkable effect was shown by Fresnel, in which a very small source of light was used to cast a shadow of a circular disc. On examining the shadow of the disc it was found that the shadow was to some extent illuminated and that the central portion of the shadow was brighter than the outlying portions. The illumination inside the geometrical shadow is of course entirely due to light diffracted round the edges of the circular disc, and

the illumination has its maximum value at the centre of the shadow.

If an exceedingly fine pencil of light is obtained by passing it through a narrow slit (Fig. 47), the amount of spreading out is so great that instead of proceeding as a fine feather in the direction of propagation it spreads out in the form of a complete fan. Diffraction is here demonstrated in an extreme form. In considering the image produced by a lens of larger aperture, the diffraction effect, although not so great, must be taken into consideration. Suppose the lens C D (Fig. 48) to be a lens forming an image of a distant star at a point B. The lens, if perfectly corrected, will refract the majority of the light so as to pass through the point B, but a certain proportion of diffracted light is given off as a haze from the beam, which will form a halo around the point. This halo, emerging from the envelope of the cone C B D, spreads out in a mist which might be expected to be uniformly distributed, but that is not so, for the individual portions of this mist of diffracted light influence their immediate neighbours and the mist arrives at the focal plane G F E B E′ F′ G′, not as a faint halo but in the form of a pattern, the size and shape of which depends upon the nature of the beam of direct light from which the diffraction has originated, and the shape and size of this pattern is of great importance when considering the question of image formation. This image of a point formed by an instrument has been called a diffraction pattern by some, an antipoint by others. The study of the antipoint produced by a perfectly corrected microscope gives the key to its power of showing fine detail.

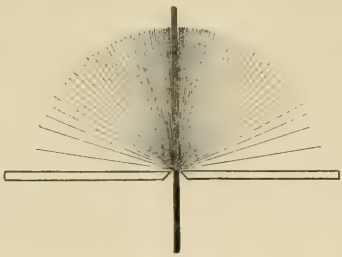


Fig. 47.

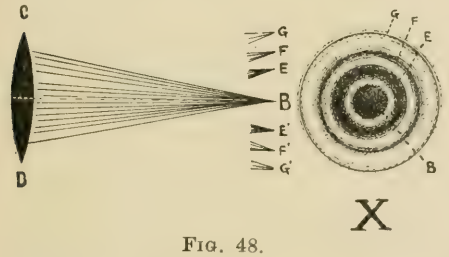


Fig. 48.

In Fig. 48 is shown at X a very highly enlarged diagram of the antipoint formed by a solid circular cone of light. A more correct and somewhat less highly magnified picture of such an antipoint is shown in Fig. 60 (*a*). It consists of a central disc brightest in the centre and gradually shading off to blackness, around which are a series of rings. As, however, the first ring is much fainter

than the central disc, and each consecutive ring much fainter than the last, it is only under exceptional circumstances that more than one ring can be seen, and for many purposes the rings can be neglected as having little or no perceptible influence on the image; consequently, attention may be confined to the diameter of the central patch or disc. It is evident that the smaller the disc the sharper the image, and it is important to ascertain what is the factor governing the size of this disc.

Recollecting the cause of diffraction, namely, that rays of light travel in direct straight lines only when there is a sufficient body of them travelling together, it is evident that the greater the number of rays there are the less is the proportion that wanders off from the direct course, and the less will be the diffraction. Thus a large cone of light, as at Fig. 49 (1), has little diffraction and produces a small disc image; a small cone of light, as at (2) or (3), will have great diffraction and produce a larger disc.

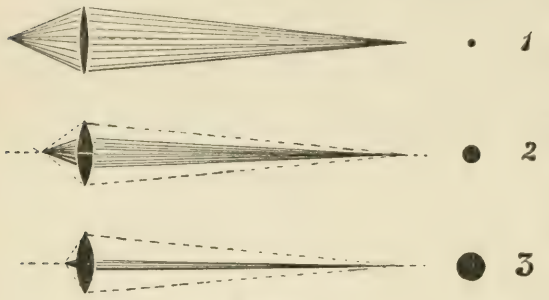


Fig. 49.

Although the bright and dark rings may not always affect the image itself, they are useful in measuring the size of the central disc, because the larger the diameter of the rings the larger will be that of the central disc, and the central disc which shades off from light to black has an indistinct outline and is difficult to measure. The most convenient portion of the diffraction pattern by which to determine the diameter is either the first black or the first bright ring. The diameter of the first dark ring may be considered as being about double that of the visible disc seen with ordinary illumination. It is worth while to form an idea of the way in which these diffraction images are formed.

Let us consider a transparent line in an otherwise black field, which is represented in Fig. 50 (1) in section, illuminated by a parallel bundle of light, X. The light, after it has passed through the aperture formed by the transparent line, consists of a direct bundle of light, surrounded by a complete fan of diffracted light. It is only a convenient method of expression to call the light (A) direct, and to call the other portions of the fan diffracted light. It is all of exactly the same kind, but had ceased to travel in a direct course, and has been spread out into a fan. If a screen be placed at any position F, there will not be, as might be supposed,

an evenly illuminated bright surface, but a series of bright and dark bands of light parallel with the slit, as shown in the upper part of the diagram. By investigating the light that reaches the centre of one of these dark bands at C, the reason for this darkness is explained.

Fig. 50 (2) is an enlarged diagram of a portion of Fig. 45 (1) showing at N″ in section the centre of one of the black bands on the screen placed at F. The whole of the light that can reach the point marked N″ is included in the beam N N″ M. Now if we consider the two boundary rays alone it will be seen that if the

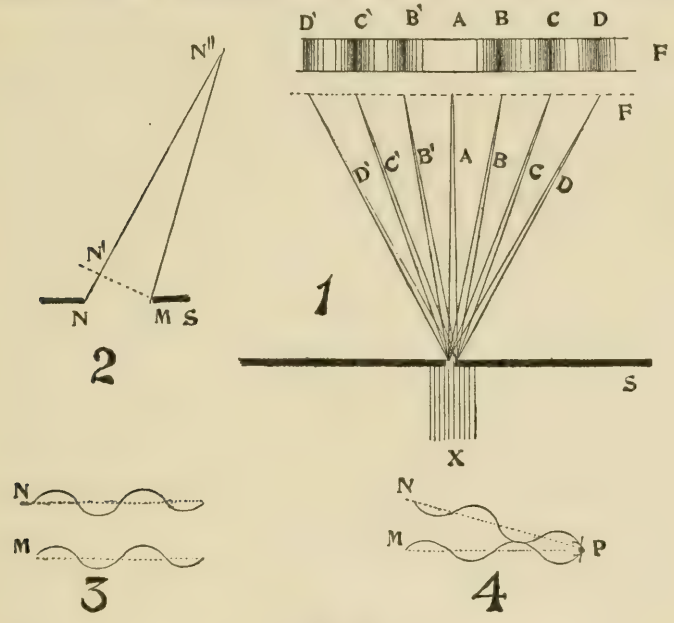


Fig. 50.

length of the ray N, N″, be compared with the length of the ray M N″, the former is longer than the latter by the amount of N N′ and that this difference will vary in length according to the obliquity of the bundle of light selected. Suppose that the distance N N′ is equal to half a wave length of light, and that the rays N and M started from the aperture in the same phase as Fig. 50 (3). When these two vibrations meet at the focus at N″ they will impinge upon the same particle of ether as shown in Fig. 50 (4); but one vibration, having travelled half a wave length further, will be half a wave length in advance of the other; thus the vibration M will strike the particle P with a tendency to force it upwards, and the other, N, will strike it with an exactly equal tendency to force it downwards, and the two vibrations

will be neutralised, thus extinguishing the light and causing darkness. This is what happens as regards a pair of separate rays, but the image is here formed by a small complete bundle; and if we suppose such a bundle to consist of, say, 10 rays close together, as at Fig. 51, and if we suppose the distance 1 C is half a wave longer than the distance 6 C, then the rays 1 and 6 will cancel each other; again, the rays 2 and 7, 3 and 8, etc., will cancel one another, so that if the distance in length between the marginal rays 1 C and 10 C is equal to one whole wave length, the entire bundle will cancel one another, and a black patch will be formed. Thus the position, where a complete bundle of rays will entirely cancel one another, will be where it is at such an angle that the two marginal rays differ in length by one complete wave length.

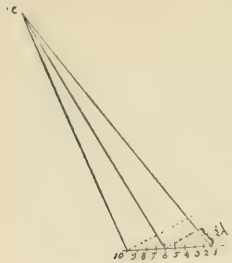


FIG. 51.

A simple proof will give the position at which the first dark image formed by a slit aperture upon a screen will be formed.

Let C D, Fig. 52, represent the slit and A B the screen; from the centre of the slit draw a line E A meeting the screen at right angles at A. If the first dark image is formed at B it will be because the line C B is one wave length (λ) longer than the line D B. Join E B and draw a line F D at right angles to B E. The length F E may then be considered to be half a wave length.

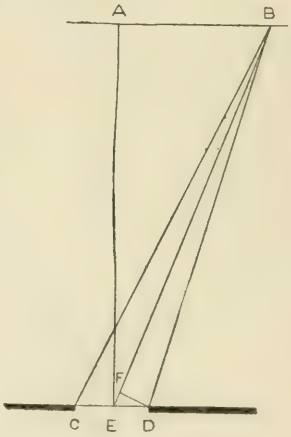


FIG. 52.

In the triangles D E F, E A B the angles E F D and E A B are right angles, and the angles A E B and E D F are equal.

$$\frac{AB}{EB} = \frac{EF}{ED}$$

$$\frac{AB}{EF} = \frac{EB}{ED}$$

As the distance from A to E is very large compared with C D, the angle E D B is almost a right angle. If we call the angle E B D, θ, $\frac{EB}{ED}$ may be considered to be equal to $\frac{1}{\sin \theta}$, and as E F is equal to $\frac{\lambda}{2}$ and if we call the distance A B $= r$

$$r = \frac{\lambda}{2 \sin \theta}$$

The second dark image will be found at a position $r = \frac{2\lambda}{2 \sin \theta}$, and so on.

When the angle θ is small, which is almost always the case, it may be considered equal to the angle E A D and

$$\frac{1}{2 \sin \theta} = \frac{A E}{C D};$$

that is, the distance of the screen from the slit divided by the width of the slit.

A slit aperture forms a series of fine dark and bright bands. A square aperture forms bright and dark bands in two directions, crossing each other at right angles, and the result is a square central patch with bright spots extending from it in directions at right angles, forming a cross of rectangular spots. If the aperture is circular the pattern is in the form of a central bright disc surrounded by bright rings. The calculation of their distance is more complex, but follows the line given, the only difference in the final equation being that $r = \frac{1 \cdot 2\lambda}{2 \sin \theta}$.

If light forming an image by a lens is considered in the same manner as light passing through a small aperture, the results are the same. The aperture C D, Fig. 52, corresponds to the margin of the lens and the plane A B corresponds to the plane of the image formed by the lens. The patterns of a point image produced are the same whether the aperture is that of a lens or not.

Consideration will be given later to antipoints produced by apertures of different shapes, but the usual case is that in which the aperture is circular and in which the image of each point is formed by a solid cone of light. The first point to be specially noted is that the size of the disc image of a point depends on the size of the cone forming the image; thus a wide cone, (1) Fig. 49, gives a small disc, a narrow cone, (3) Fig. 49, gives a large disc.

In order that an image of a point may appear to be a point the disc must be below the size that the eye can recognise as having a definite size, so that if the image is much magnified, then the angle of the cone forming the image must be great, and a narrow cone cannot be used if much magnifying power is required. The amount of magnifying power that can be usefully employed depends upon how large a cone of light can be used to form the image. The size of this cone depends upon the size or aperture of the lens or object-glass which forms the primary image in the microscope. It is assumed throughout the discussion on resolution that the object-glasses are perfectly corrected and are free from aberrations; with first-class microscope lenses, especially of the apochromatic type, this condition has been approximately fulfilled.

Every optical instrument has an aperture. It admits light to a greater or lesser extent, according to whether its aperture is larger or smaller. In a telescope the aperture is limited by the margin of the lenses which form the object-glass, unless for some definite reason there is a diaphragm introduced in some position to exclude some of the light that would otherwise pass through the instrument. The aperture is in this case expressed by the diameter of the object-glass apart from any other properties the telescope may possess. It may be 5, 20, or 30 inches diameter, and will collect from a star more light, in the proportion of the area of its object-glass, so that stars that are too feeble to be visible to the naked eye are rendered visible because a larger quantity of light is collected from them by means of a telescope with a large object-glass. The importance of the aperture of the telescope is to increase light, and is measured only by the diameter of the beam of light which it collects. No fixed star is magnified even with the largest telescope; it still appears to be a point apart from any spreading that may be caused by diffraction.

The aperture of a microscope is of importance, but not because it collects a large quantity of light. There is usually no difficulty in obtaining as much intensity as is required by employing a powerful illuminant. It must collect a wide angle cone of light. Fig. 49 illustrates that in order to form an image by means of a large cone of light, the object-glass of a microscope must be large compared with its focal length. The larger the angle of the cone of light the less the diffraction, the smaller the cone the greater the diffraction, and it is for this reason and not for the obtaining of increased intensity that the aperture in the microscope is important.

So far we have only considered the image of a point formed by a lens. Microscopic objects are seldom points, but every object may be considered to be a mass of points in close proximity. The simplest of such objects is a line which if sufficiently fine may be considered to be a row of single points. If a particular lens depicts each of these points as a disc bright in the centre and fading off at the edge, then the same lens will show a fine line as a row of discs overlapping one another which will appear as a band of perceptible width with the centre slightly brighter than the edges, the width of the band being the same as the diameter of the disc. It is interesting to examine the conditions under which two parallel lines in an object can be recognised as being two and not one line in the image. The image of each line is a band with a definite width $\left(r = \frac{1 \cdot 2\lambda}{2 \sin \theta}\right)$ and not a line; and if the bands are of the same width as their distance apart, then their edges will just meet. A band of double the width will be seen instead of two bands. The two bands may not be quite so

bright along their extreme edges where they meet, but except for this it will not be possible to tell that they are pictures of two lines. If the edges of the two bands do not meet there will be a space between them, and it can be recognised that there are two lines. Such lines are said to be resolved, and the resolving power of a microscope is expressed by the distance apart of the lines that can just be observed as separated lines, 20,000, 40,000, 60,000 lines to the inch, and so on. If a microscope will resolve straight lines of a particular separation it will resolve dots, hairs, or curved lines separated by a similar amount. It will show single lines, dots, or hairs of a smaller size than this, but their images will be broader and less distinct than the objects which they depict. If a lens will only resolve lines 20,000 to the inch, then a single line will be shown by that lens about 1/20,000 of an inch broader than the object itself, and therefore, the number of lines to the inch that a lens will separate is a fair method of expressing its resolving power.

The resolving power of a lens, therefore, depends on the size of the diffraction disc or antipoint which it forms; this depends on the size of the cone of light which forms the image; but the resolution also depends on the magnifying power. Fig. 53 shows two lenses with different magnifying power, one of which gives twice the diffraction of the other; but as it also gives twice the magnification it produces the same resolution.

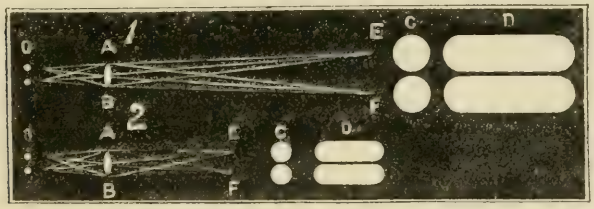


Fig. 53.

Suppose two points or lines at O are the same distance apart in the diagrams (1) and (2), but in (1) the distance from A B to E F is double that in (2), then the magnifying power in (1) is double that in (2). The angle of the light forming the image is half as great in (1) as in (2), and the diffraction disc (C) is twice as large as that of (2). But the magnification is also double, and the effect as regards separating lines is the same in both cases, the large and small images (D) in both cases being just resolved. To ascertain resolving power it is therefore necessary to consider the diffraction and the magnifying power. It will, however, be seen that in order to obtain the double magnifying power of (1) as compared with (2) the distance of the image E F

from the lens is double, while the angle of the light from the object to the lens is the same in both cases. The measurement of this angle gives the amount of diffraction compared with the magnification : it is a combined measurement of the diffraction and the magnifying power and is, therefore, the measurement of the resolution of the lens.

If, therefore, we consider the angle of the light that enters the lens and not the angle of the light that actually forms the image, it is a measurement of the resolution of the lens independent of the magnifying power. A lens that will collect a particular angle of light is capable of resolving lines of a particular distance apart and nothing closer. The magnifying power may or may not be enough to render them visible to the eye, but they are there as separate lines in the image and are capable of being photographed on a plate with a fine emulsion, or of being seen if a higher-power eyepiece be used to examine the primary image.

A somewhat closer investigation may be made into the conditions which connect the angle of light which enters the lens with the cone of light which forms the image. It has been shown that the half-diameter of the black ring round the diffraction disc, which may be considered as being about the diameter of the disc, is expressed by the formula

$$r = \frac{1 \cdot 2\lambda}{2 \sin \theta}, \qquad (1)$$

where θ is equal to half the angle of the cone of light forming the image and not of the light as it enters the object-glass.

Fig. 54 shows a diagrammatic microscope object-glass in which the lens system has been replaced by its Gauss surfaces. It will be remembered that as microscope object-glasses fulfil the sine condition those surfaces will be spherical about the conjugate foci for which they are aplanatic.

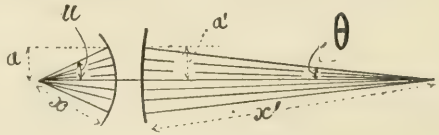


Fig. 54.

It is necessary to convert the above formula (1) into a form that expresses the size of the diffraction disc in relation to magnifying power (M).

In the above diagram $\frac{x}{x'} = \frac{n}{M}$ where n is the refractive index of the medium from which light is entering the object-glass, the medium on the image side being considered as air.[1]

[1] See footnote on opposite page.

$$x = \frac{a}{\sin u} \qquad x' = \frac{a'}{\sin \nu} \quad a = a'$$

$$\frac{x}{x'} = \frac{n}{\mathrm{M}} = \frac{\dfrac{a}{\sin u}}{\dfrac{a'}{\sin \theta}}$$

$$\therefore \sin \theta = \frac{n \sin u}{\mathrm{M}};$$

and inserting this in formula (1).

$$r = \frac{1.2 \lambda \mathrm{M}}{2n \sin u}. \qquad (2)$$

This measurement is not only the diameter of the diffraction disc, but is the measurement of the distance apart of two lines in the image that can just be resolved. The distance apart of the actual lines in the object from which this image is produced by the microscope will be the above expression divided by the

---

NOTE.—The fact that the magnification of an image is influenced by the refractive index of the medium on one side of a lens compared with that on the other, $\frac{x}{x'} = \frac{n}{\mathrm{M}}$ may not be familiar to those who are accustomed to read textbooks in which it is assumed that the media on each side of a lens are always air, and it may be worth while to illustrate the point by a diagram. Suppose the upper diagram (Fig. 55) to represent a thin lens, the space on either side of which is air. Then, if the lens is thin, the rays O I and O′I′ go directly through the centre of the lens,

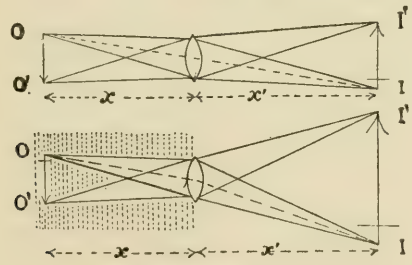


FIG. 55.

and the magnification $\frac{\mathrm{I\,I'}}{\mathrm{O\,O'}}$ is equal to $\frac{x'}{x}$; but suppose that the medium on the left of the lens is of a high refractive index, n, and on the right air, then these two rays O I and O I′ will be bent outwards at the lens, and the magnifying power $\frac{\mathrm{I\,I'}}{\mathrm{O\,O'}}$ will be equal to $\frac{nx'}{x}$. The proof will be found in such books as *Dioptric Instruments*, published by H. M. Stationery Office.

magnifying power M. The resolution (R) is therefore given by the formula

$$R = \frac{1.2\,\lambda}{2n \sin u}. \qquad (3)$$

The expression $n \sin u$ is known to microscopists under the name of Numerical Aperture (N.A.), and

$$R = \frac{1.2\,\lambda}{2\ \text{N.A.}}. \qquad (4)$$

The examination of this formula shows that if the numerical aperture of a microscope object-glass is known the finest lines that it is capable of resolving is known for any given wave length of light.

The quantity called numerical aperture ($n \sin u$) is the only factor which governs resolution with an aperture of a circular shape apart from the wave length of light, though the visibility also depends upon the particular degree of contrast in brilliancy which the eye requires in order to differentiate objects. If one lens has a numerical aperture double that of another, it will resolve lines twice as fine. That in itself is an advantage in using such an expression as Numerical Aperture, because a lens that has double the aperture measured in degrees will not resolve exactly double the number of lines to the inch; for instance, an angle of 80° will resolve 68,000 lines to the inch, an angle of 160°, only 103,000. The chief advantage, however, of using this expression rather than the actual angle is that it also is applicable to the use of immersion object-glasses, when the whole of the medium between the object and the object-glass is composed of a high refracting medium. In this case the size of the diffraction disc may be the same as it is when air is the medium in which the object is situated, but the magnification is more, and the resolution is therefore greater, because the images of two points are the same in size but separated to a greater extent. Thus the one expression Numerical Aperture ($n \sin u$) divided into the half-wave length of light, gives the size of the diffraction disc and its relation to the magnification of the image.

The following table is taken from the *Journal of the Royal Microscopical Society.*

APERTURE TABLE

Numerical Aperture ($n \sin u = a$).	Corresponding Angle ($2u$) for			Limit of Resolving Power, in Lines to an Inch.		
	Air ($n = 1{\cdot}00$).	*Water* ($n = 1{\cdot}33$).	*Homogeneous Immersion* ($n = 1{\cdot}52$).	White Light. ($\lambda = 0{\cdot}5269\ \mu$, Line E.)	Monochromatic (Blue) Light. ($\lambda = 0{\cdot}4861\ \mu$, Line F.)	Photography. ($\lambda = 0{\cdot}4000\ \mu$, near Line *h*.)
1·52	..	..	180° 0′	146,543	158,845	193,037
1·51	..	..	166° 51′	145,579	157,800	191,767
1·50	..	..	161° 23′	144,615	156,755	190,497
1·49	..	..	157° 12′	143,651	155,710	189,227
1·48	..	..	153° 39′	142,687	154,665	187,957
1·47	..	..	150° 32′	141,723	153,620	186,687
1·46	..	..	147° 42′	140,759	152,575	185,417
1·45	..	..	145° 6′	139,795	151,530	184,147
1·44	..	..	142° 39′	138,830	150,485	182,877
1·43	..	..	140° 22′	137,866	149,440	181,607
1·42	..	..	138° 12′	136,902	148,395	180,337
1·41	..	..	136° 8′	135,938	147,350	179,067
1·40	..	..	134° 10′	134,974	146,305	177,797
1·39	..	..	132° 16′	134,010	145,260	176,527
1·38	..	..	130° 26′	133,046	144,215	175,257
1·37	..	..	128° 40′	132,082	143,170	173,987
1·36	..	..	126° 58′	131,118	142,125	172,717
1·35	..	..	125° 18′	130,154	141,080	171,447
1·34	..	..	123° 40′	129,189	140,035	170,177
1·33	..	180° 0′	122° 6′	128,225	138,989	168,907
1·32	..	165° 56′	120° 33′	127,261	137,944	167,637
1·31	..	160° 6′	119° 3′	126,297	136,899	166,367
1·30	..	155° 38′	117° 35′	125,333	135,854	165,097
1·29	..	151° 50′	116° 8′	124,369	134,809	163,827
1·28	..	148° 42′	114° 44′	123,405	133,764	162,557
1·27	..	145° 27′	113° 21′	122,441	132,719	161,287
1·26	..	142° 39′	111° 59′	121,477	131,674	160,017
1·25	..	140° 3′	110° 39′	120,513	130,629	158,747
1·24	..	137° 36′	109° 20′	119,548	129,584	157,477
1·23	..	135° 17′	108° 2′	118,584	128,539	156,207
1·22	..	133° 4′	106° 45′	117,620	127,494	154,937
1·21	..	130° 57′	105° 30′	116,656	126,449	153,668
1·20	..	128° 55′	104° 15′	115,692	125,404	152,397
1·19	..	126° 58′	103° 2′	114,728	124,359	151,128
1·18	..	125° 3′	101° 50′	113,764	123,314	149,857
1·17	..	123° 13′	100° 38′	112,799	122,269	148,588
1·16	..	121° 26′	99° 29′	111,835	121,224	147,317
1·15	..	119° 41′	98° 20′	110,872	120,179	146,048
1·14	..	118° 0′	97° 11′	109,907	119,134	144,777
1·13	..	116° 20′	96° 2′	108,943	118,089	143,508
1·12	..	114° 44′	94° 55′	107,979	117,044	142,237
1·11	..	113° 9′	93° 47′	107,015	115,999	140,968
1·10	..	111° 36′	92° 43′	106,051	114,954	139,698
1·09	..	110° 5′	91° 38′	105,087	113,909	138,428
1·08	..	108° 36′	90° 34′	104,123	112,864	137,158
1·07	..	107° 8′	89° 30′	103,159	111,819	135,888
1·06	..	105° 42′	88° 27′	102,195	110,774	134,618
1·05	..	104° 16′	87° 24′	101,231	109,729	133,348
1·04	..	102° 53′	86° 21′	100,266	108,684	132,078

APERTURE TABLE—*continued*

Numerical Aperture ($n \sin u = a$).	Corresponding Angle ($2u$) for			Limit of Resolving Power, in Lines to an Inch.		
	Air ($n = 1{\cdot}00$).	*Water* ($n = 1{\cdot}33$).	*Homogeneous Immersion* ($n = 1{\cdot}52$).	White Light ($\lambda = 0{\cdot}5269\ \mu$, Line E.)	Monochromatic (Blue) Light. ($\lambda = 0{\cdot}4861\ \mu$, Line F.)	Photography. ($\lambda = 0{\cdot}4000\ \mu$, near Line *h*.)
1·03	..	101° 30′	85° 19′	99,302	107,639	130,808
1·02	..	100° 10′	84° 18′	98,338	106,593	129,538
1·01	..	98° 50′	83° 17′	97,374	105,548	128,268
1·00	180° 0′	97° 31′	82° 17′	96,410	104,503	126,998
0·99	163° 48′	96° 12′	81° 17′	95,446	103,458	125,728
0·98	157° 2′	94° 56′	80° 17′	94,482	102,413	124,458
0·97	151° 52′	93° 40′	79° 18′	93,518	101,368	123,188
0·96	147° 29′	92° 24′	78° 20′	92,554	100,323	121,918
0·95	143° 36′	91° 10′	77° 22′	91,590	99,278	120,648
0·94	140° 6′	89° 56′	76° 24′	90,625	98,233	119,378
0·93	136° 52′	88° 44′	75° 27′	89,661	97,188	118,108
0·92	133° 51′	87° 32′	74° 30′	88,697	96,143	116,838
0·91	131° 0′	86° 20′	73° 33′	87,733	95,098	115,568
0·90	128° 19′	85° 10′	72° 36′	86,769	95,053	114,298
0·89	125° 45′	84° 0′	71° 40′	85,805	93,008	113,028
0·88	123° 17′	82° 51′	70° 44′	84,841	91,963	111,758
0·87	120° 55′	81° 42′	69° 49′	83,877	90,918	110,488
0·86	118° 38′	80° 34′	68° 54′	82,913	89,873	109,218
0·85	116° 25′	79° 37′	68° 0′	81,949	88,828	107,948
0·84	114° 17′	78° 20′	67° 6′	80,984	87,783	106,678
0·83	112° 12′	77° 14′	66° 12′	80,020	86,738	105,408
0·82	110° 10′	76° 8′	65° 18′	79,056	85,693	104,138
0·81	108° 10′	75° 3′	64° 24′	78,092	84,648	102,868
0·80	106° 16′	73° 58′	63° 31′	77,128	83,603	101,598
0·79	104° 22′	72° 53′	62° 38′	76,164	82,558	100,328
0·78	102° 31′	71° 49′	61° 45′	75,200	81,513	99,058
0·77	100° 42′	70° 45′	60° 52′	74,236	80,468	97,788
0·76	98° 56′	69° 42′	60° 0′	73,272	79,423	96,518
0·75	97° 11′	68° 40′	59° 8′	72,308	78,378	95,248
0·74	95° 28′	67° 37′	58° 16′	71,343	77,333	93,979
0·73	93° 46′	66° 34′	57° 24′	70,379	76,288	92,709
0·72	92° 6′	65° 32′	56° 32′	69,415	75,242	91,439
0·71	90° 28′	64° 32′	55° 41′	68,451	74,197	90,169
0·70	88° 51′	63° 31′	54° 50′	67,487	73,152	88,899
0·69	87° 16′	62° 30′	53° 59′	66,523	72,107	87,629
0·68	85° 41′	61° 30′	53° 9′	65,559	71,062	86,359
0·67	84° 8′	60° 30′	52° 18′	64,595	70,017	85,089
0·66	82° 36′	59° 30′	51° 28′	63,631	68,972	83,819
0·65	81° 6′	58° 30′	50° 38′	62,667	67,927	82,549
0·64	79° 36′	57° 31′	49° 48′	61,702	66,882	81,279
0·63	78° 6′	56° 32′	48° 58′	60,738	65,837	80,009
0·62	76° 38′	55° 34′	48° 9′	59,774	64,792	78,739
0·61	75° 10′	54° 36′	47° 19′	58,810	63,747	77,469
0·60	73° 44′	53° 38′	46° 30′	57,846	62,702	76,199
0·59	72° 18′	52° 40′	45° 40′	56,881	61,657	74,929
0·58	70° 54′	51° 42′	44° 51′	55,918	60,612	73,659
0·57	69° 30′	50° 45′	44° 2′	54,954	59,567	72,389
0·56	68° 6′	49° 48′	43° 14′	53,990	58,522	71,119
0·55	66° 44′	49° 51′	42° 25′	53,026	57,477	69,849

APERTURE TABLE—*continued*

Numerical Aperture ($n \sin u = a$).	Corresponding Angle ($2u$) for			Limit of Resolving Power, in Lines to an Inch.		
	Air ($n = 1{\cdot}00$).	*Water* ($n = 1{\cdot}33$).	*Homogeneous Immersion* ($n = 1{\cdot}52$).	White Light. ($\lambda = 0{\cdot}5269\ \mu$, Line E.)	Monochromatic (Blue) Light. ($\lambda = 0{\cdot}4861\ \mu$, Line F.)	Photography. ($\lambda = 0{\cdot}4000\ \mu$, near Line *h*.)
0·54	65° 22′	47° 54′	41° 37′	52,061	56,432	68,579
0·53	64° 0′	46° 58′	40° 48′	51,097	55,387	67,309
0·52	62° 40′	46° 2′	40° 0′	50,133	54,342	66,039
0·51	61° 20′	45° 6′	39° 12′	49,169	53,297	64,769
0·50	60° 0′	44° 10′	38° 24′	48,205	52,252	63,499
0·48	57° 22′	42° 18′	36° 49′	46,277	50,162	60,959
0·46	54° 47′	40° 28′	35° 15′	44,349	48,072	58,419
0·45	53° 30′	39° 33′	34° 27′	43,385	47,026	57,149
0·44	52° 13′	38° 38′	33° 40′	42,420	45,981	55,879
0·42	49° 40′	36° 49′	32° 5′	40,492	43,891	53,339
0·40	47° 9′	35° 0′	30° 31′	38,564	41,801	50,799
0·38	44° 40′	33° 12′	28° 57′	36,636	39,711	48,259
0·36	42° 12′	31° 24′	27° 24′	34,708	37,621	45,719
0·35	40° 58′	30° 30′	26° 38′	33,744	36,576	44,449
0·34	39° 44′	29° 37′	25° 51′	32,779	35,531	43,179
0·32	37° 20′	27° 51′	24° 18′	30,851	33,441	40,639
0·30	34° 56′	26° 4′	22° 46′	28,923	31,351	38,099
0·28	32° 32′	24° 18′	21° 14′	26,995	29,261	35,559
0·26	30° 10′	22° 33′	19° 42′	25,067	27,171	33,019
0·25	28° 58′	21° 40′	18° 56′	24,103	26,126	31,749
0·24	27° 46′	20° 48′	18° 10′	23,138	25,081	30,479
0·22	25° 26′	19° 2′	16° 38′	21,210	22,991	27,940
0·20	23° 4′	17° 18′	15° 7′	19,282	20,901	25,400
0·18	20° 44′	15° 34′	13° 36′	17,354	18,811	22,860
0·16	18° 24′	13° 50′	12° 5′	15,426	16,721	20,320
0·15	17° 14′	12° 58′	11° 19′	14,462	15,676	19,050
0·14	16° 5′	12° 6′	10° 34′	13,498	14,630	17,780
0·12	13° 47′	10° 22′	9° 4′	11,570	12,540	15,240
0·10	11° 29′	8° 38′	7° 34′	9,641	10,450	12,700
0·08	9° 11′	6° 54′	6° 3′	7,713	8,360	10,160
0·06	6° 53′	5° 10′	4° 32′	5,785	6,270	7,620
0·05	5° 44′	4° 18′	3° 46′	4,821	5,225	6,350

It gives in the first column numerical apertures ; in the second, third, and fourth columns the corresponding angles of $2u$, the incident light in air, water, and glass ; and in the fifth and sixth columns values of R for three different colours. The values of R given in the table are not worked out strictly on the above formula, as it is considered by some that the size of the diffraction disc as measured by $R = \frac{1.2\,\lambda}{2\ N.A.}$ is rather too large a value on account of the fact that the light at the edge of the diffraction disc is faint, and the actual formula taken to work out the table is $R = \frac{\lambda}{2\ N.A.}$.

This appears to correspond very accurately with practice.

It will be noticed that in the Table of Resolution the value of numerical aperture is expressed in angles in air, water, and glass. That is to say, the values of $2u$ are given when the refractive index (n) for air is 1, for water 1·33, and for crown glass 1·52. The fact that such angles are equivalent may be illustrated by a diagram, Fig. 56. Suppose a beam of light having an angle of 72½°, or ·9, N.A. is emerging from glass into air, when it is in air it has been refracted and has an angle of 128°, but still has a N.A. of ·9. If it re-enters glass it again has its original angle; it retains the same N.A. throughout, and has the same resolving power whether it is in glass or air, although its angle has changed.

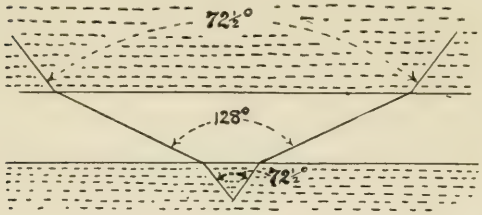


Fig. 56.

Fig. 57.

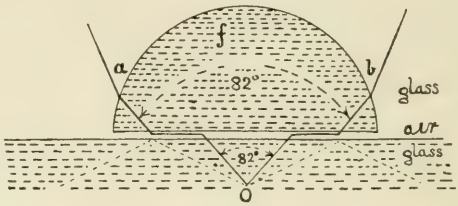


Fig. 58.

Suppose the angle to be 82° in glass (1 N.A.), Fig. 57, it will emerge into air at an angle of 180° (1 N.A.) and no greater angle can enter from the glass into the air. If light at a greater angle than 82°, such as indicated by the dotted line, Fig. 57, tries to pass from the glass into the air it is completely reflected back and does not emerge. If we suppose f, Fig. 58, to represent the front lens of a dry microscope object-glass, in which case there is a layer of air between it and the object, and Fig. 59 an immersion

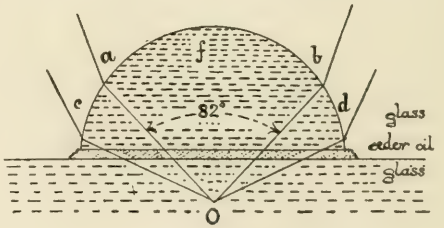


Fig. 59.

object-glass, where this air space is filled up with cedar wood oil which for optical purposes may be considered as liquid glass, it is evident that no light from an object situated at O in Fig. 58, where there is a layer of air, can enter the lens of a greater angle than 180°, and the light emerges to form the image from the lens (*f*) in a cone having a base (*a b*), but if the whole space between the object and the lens is glass, a larger angle of light from O, in the case shown in Fig. 59, will enter the lens, and the light forming the image will be formed by a larger cone of rays *c d*, giving greater resolving power.

This chapter has so far been devoted to showing that the larger the aperture of a microscope the more perfect will be the image; that the angular size of the bundle of light collected by the object-glass from each point of the object is the factor that determines the degree of resolution; that with immersion lenses a greater effective angle can be obtained; and that the term Numerical Aperture is a true means of expressing the resolving power of the microscope. We have, however, assumed that the aperture is circular and that the whole aperture is being made use of. This is not always the case; the aperture may not always be circular in shape, and even when it is, it is not always evenly filled with light. The illumination may be such that light is only passing through certain portions, and in such a case the diffraction will be the same as if the aperture were of the shape of those portions of it which are actually in use.

For this reason the antipoint, or diffraction, images of a point formed by lenses with apertures of different shapes deserve more careful attention than has generally been given to them.

Figs. 60, 61, 62, 63 are illustrations of the diffraction patterns of a point which are produced by a microscope object-glass which has apertures of different shapes. The illustrations are drawn to scale from the observed appearances and are all magnified to the same extent. They cannot be satisfactorily photographed, as the exposure required for the fainter portions obscures the brilliant parts. A thin silver film with a very minute hole formed the object. It was examined with an eyepiece magnifying 50, and an 8 mm. apochromatic object-glass having a numerical aperture of ·65 N.A. Diaphragms giving apertures of the shapes indicated were inserted near the back focal plane of the object-glass. The measurements were taken with a travelling cobweb micrometer eyepiece. The measurements of such small objects are difficult, and are not so accurate as if they had been calculated, but they are more convincing if taken from the actual images and are in substantial agreement with theory.

Each image is that of a point, the only difference being the aperture of the lens through which it is viewed. By the side of each antipoint is illustrated the appearance of a line, or in some cases

of two lines, at right angles to each other, viewed with the same aperture. A line is a row of points in close juxtaposition, and it would be possible to construct the appearance analytically from the image of a point, but it has been considered better to reproduce the appearances as observed. Some of the supplementary details in the antipoint are so faint that they cannot be easily seen and have not been illustrated, and in the images of the lines no attempt has been made to show any but the brilliant portions of the image.

There are cases where portions of the image which are of the second order of brightness have some influence on the resolution of the microscope, but only when the illumination is intense or contrast is specially marked.

The definition and resolving power of a microscope are so dependent on these diffraction images that they should be carefully compared.

The illustrations are magnified 2,000 diameters; the object-glass with which they are taken, if used with a moderate eyepiece instead of the very high-power eyepiece referred to, gives a magnifying power of 150, so that if the illustrations are placed at a distance of 12 feet from the eye they will give the appearance that would be produced by apertures of these shapes and sizes in practice. The images of the line in some of the figures is as sharp as is required to give perfect definition; in others it would produce a fuzzy and indistinct picture of a line, and therefore of any other microscope object.

The antipoints of square, triangular, and other shaped apertures are curious, and in some cases beautiful patterns, but those illustrated will serve to explain the points of interest in microscopic resolution.

These phenomena are the chief factor in governing the resolution and clear delineation with the microscope. The circular aperture produces a more nearly correct image of a point than an aperture of any other shape, the only requisite is that its aperture should be large enough in proportion to the magnifying power; even the tiny aperture, Fig. 60*b*, if the image were only magnified, say, 10 diameters, would give an image that could not be distinguished from a point, but when the magnifying power is increased to the amount shown in the diagram it is seen to be a large disc. A useful rule may be formulated from the size of these discs and the formula for resolution given on page 66. If two lines are 1/150th inch apart they can be easily resolved with the naked eye at a distance of 10 inches. In order that the lines should be thus resolved by a microscope the diffraction disc in the final image should not be larger than 1/150th of an inch. If a magnifying power of 100 be used the eye will be capable of seeing lines 1/15,000th of an inch apart.

The numerical aperture required to give resolution of

FIG. 60 *a* shows the image of a point formed by a large aperture, (·65 N.A.). It consists of a very minute disc surrounded by a few faint rings which, except under special circumstances, are invisible, and the image of a line is a band so thin that it appears to be a fine line.

FIG. 60 *b* shows the image formed by a very small aperture, ·08 N.A. It has a large central disc and large rings, one only of which is shown. The image of a line is a fuzzy band of considerable size. The breadth is eight times as broad as that of the full aperture image (*a*), and a lens must have an aperture considerably larger than ·08 N.A. to give a sharp picture with anything but an extremely small magnifying power.

FIG. 60 *c* shows the image formed by an annular-ring aperture when inner and outer diameters are ·65 N.A. and ·5 N.A. The central spot is small, but the rings, or some of them, are almost as bright as the central spot, and the result on the image of a line is almost as bad as that of a small aperture. The brilliancy of the surrounding rings is dependent on the width of the annular aperture. The smaller the thickness of the annular ring the more brilliant the lines. Therefore, this form of aperture is not usually satisfactory.

FIG. 61 *d* shows the antipoint produced by an aperture ·65 N.A., which is half a disc, a case that frequently occurs in practice. In the case of the old binocular microscopes and with the use of a prism vertical illuminator the aperture is obscured over half its area by the prism. The result is that lines in one direction are as sharp as with a full-aperture lens, but at right angles they are about double as broad, and the defining power of such a lens is half that of one with the full aperture.

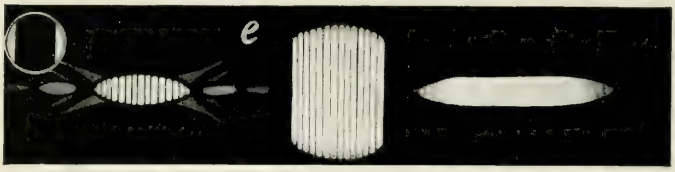


FIG. 61 *e* shows the antipoint produced when light comes through the lens through only two opposite segments of the circle. The diffraction pattern is curious, but it will be seen that the central patch is very large and crossed by black lines, and the images of a line are most unsatisfactory.

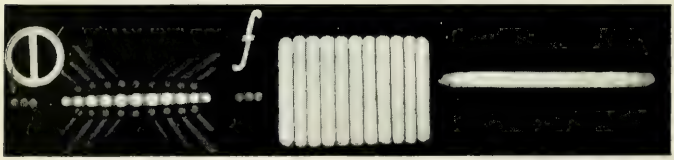
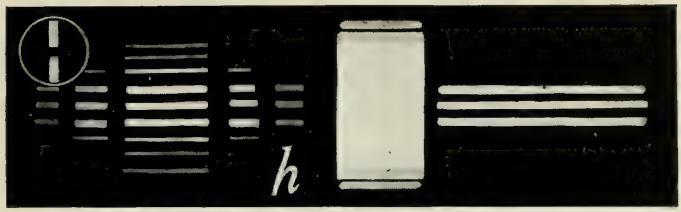


FIG. 61 *f* shows the antipoint of a lens in which the portion that is transmitting light consists of an annular and a straight slit. This aperture gives a very bad picture of a line except in one direction. It is artificially formed in high-power lenses illuminated by the edge of a lamp flame with a badly corrected substage condenser.

FIG. 62 *g* shows the antipoint produced by a slit aperture ·08 × ·65 N.A.



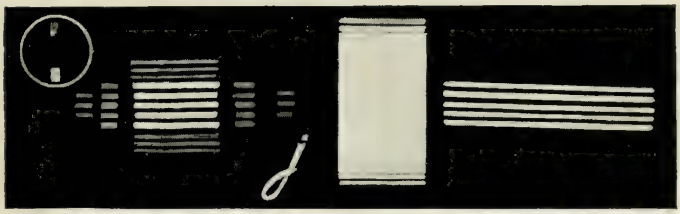


FIG. 62 *h*, *j*, *k*, show the antipoints produced by a slit aperture more or less filled up in the centre.

These are an interesting series showing how a lens with such an aperture would give very perfect images of lines in one direction only, but they give multiple images. Fig. 62 *h* would give three, Fig. 62 *j* five, Fig. 62 *k* seven lines for every line in the object; and thus, with such apertures, totally erroneous ideas might be obtained of the number of the lines in the object. At the same time, such an aperture behind the object-glass would appear to be excellent for examining fine rulings, provided it were placed at right angles to the direction of the lines, because the thickness of the lines in that direction is actually less than those seen by the full aperture, Fig. 60 *a*. If placed in any other direction compared with the lines it destroys the image completely.

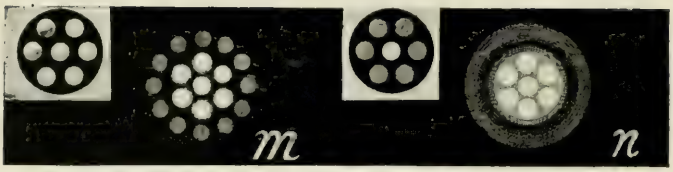


Fig. 63 *m* shows the pattern of the antipoint when the aperture behind the object-glass consists of one central small aperture surrounded by six others arranged symmetrically around the centre.

Fig. 63 *n* shows the pattern of the antipoint when the aperture behind the object-glass is the same as that used in Fig. 63*m*, but the intensity of the light in the centre is increased over that of the marginal portions of the aperture; the effect produced is that of Fig. 63*m* superimposed upon an antipoint that would have been produced by a small central aperture alone.

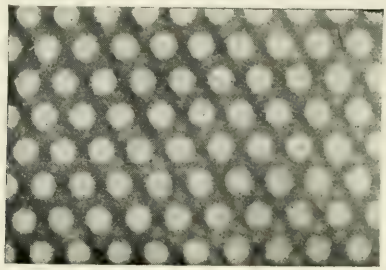


Fig. 64.—Copy of a photograph of Pleurosigma angulatum taken with a narrow-angle cone of light. The diffraction at the diatom throws off a series of beams of light which utilise the portions of the aperture in the object-glass shown in Figs. 63 *m* and 63 *n*.

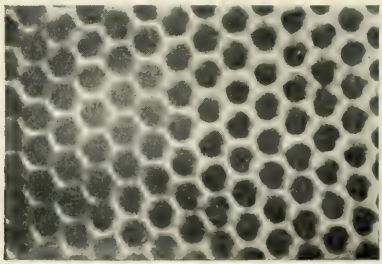


Fig. 65.—Copy of a photograph of Pleurosigma angulatum taken with the full aperture of the object-glass evenly filled with light.

1/15,000 inch is obtained from the formula $R = \frac{\lambda}{2 \text{ N.A.}}$ (page 66).

Suppose $\lambda = \frac{1}{50{,}000}$ of an inch, then

$$\frac{1}{15{,}000} = \frac{1}{100{,}000 \text{ (N.A.)}}$$

$$\text{N.A.} = \frac{15}{100} = \cdot 15 \text{ N.A.}$$

Thus for 100 magnifying power the aperture should be ·15 N.A., 200 ·3 N.A., 500 ·75 N.A., 800 1·3 N.A.

Such an aperture should be reached if possible. If the observer has not very good eyesight he may not see all the fine detail that this aperture can resolve; on the other hand, a trained observer could use a larger aperture.

Object-glasses with not less than the apertures above specified will resolve all that an ordinary observer will be likely to see. The figures are calculated on the basis that the normal eye can resolve objects whose distance apart subtends two minutes of arc. Under certain very favourable circumstances of light and shade objects can be just resolved half a minute apart, but conditions sufficiently favourable seldom occur in microscopic work.

To say that an object-glass should have an aperture of ·3 N.A. when it is usually employed with an eyepiece that gives a total magnifying power of 200 is a useful rule, but it does not follow that a higher magnifying power than 200 should not be occasionally, or even frequently, used with an object-glass which has a numerical aperture of ·3 N.A.

Many observers find it extremely tiring to look for long at very fine detail and prefer to make the magnifying power greater, not because they can see more, but because they see it with less fatigue.

It is safe to say that if the numerical aperture is multiplied by 1,000, that magnification will give a thoroughly comfortable view of the detail that will be shown by the lens possessing such an aperture.

The shape of the aperture does not appear at first sight to be of importance, because all lenses have circular apertures, the size of which determines the resolution. The semi disc, Fig. 61 *d*, becomes a practical question in the Wenham and some other binocular microscopes, where half the rays go to one eye and half to the other, and in the use of the prism vertical illuminator, but other shaped apertures are seldom met with. Such apertures are, however, artificially produced if the illumination is such that only certain portions of the complete aperture are transmitting light. Methods of illumination are in regular use, some accidental, some of set purpose, which if employed in the observation of

objects which do not in themselves scatter light, make use of only certain portions of the object-glass. If a patch stop be placed below a condenser which obstructs the central portion, then light only passes through the marginal portion of the object-glass and the effective aperture is that of Fig. 60 *c*. If a badly corrected substage condenser be used with the edge of a flame as an illuminant, the portion of the aperture of the object-glass that is used is frequently as shown in Fig. 61 *f*. If a substage condenser is out of focus there may be a small central patch and an annular ring in use, or there may be other rings of light dependent on the corrections of the condenser which will determine the amount and character of the effective aperture. Slits and portions of slits are often supplied to insert below a condenser which limit the effective aperture to portions, as shown in Fig. 62.

A well-corrected condenser, approximately in focus upon the object, will, if the aperture is large enough, always fill the aperture evenly with light, and examination of the antipoints and the depiction of lines due to them show that the best resolution and definition will always be obtained under such conditions. It is certainly the case that the use of a badly corrected condenser, unless some additional means be taken to fill the aperture of the object-glass evenly, will give unsatisfactory results. To what extent the question is modified by other factors will be seen later. The use of a slit or portions of a slit for illumination introduces an interesting subject.

Consider the case in its most extreme form, as shown in Fig. 62 *k*. Every line in the object, if it is at right angles to the two beams of light, is depicted as seven equally brilliant lines, and the breadth of these lines is even finer than when produced by the full circular aperture of the lens. If such an illumination be used to show ruled parallel lines that happen to correspond in their distance apart with the distance of the lines in the antipoint, finer lines can be resolved in this manner than by any other means. It is, however, a spurious resolution, for if in such a ruling one line were missing, the antipoint pattern would fill it in and its absence could not be detected, or if two lines only existed in the object they would appear as fourteen lines, as each line gives rise to seven in the image. This method of illumination has been largely recommended for the display of line structure in diatoms, and it is effective, but produces inaccurate results.

The use of a diaphragm, as in Fig. 63 *m*, below the condenser has not, as far as I am aware, been recommended, but it is evident that it would give an excellent dot appearance of diatom structure, which would be equally spurious. Such trick methods of illumination produce regular periodic patterns and destroy individual characteristics. The absence of a dot, any slight irregularity, any detail of structure is not detected as it is overlaid with a pattern which is only a general average of the main structure.

These remarks presuppose that the object is not scattering light, and that the portions of the lens aperture which are filled with light are dependent on the light which is passed into the object-glass by the condenser.

Such remarks obviously do not apply to objects which are illuminated on a dark ground and which become radiant objects scattering light in all directions. The whole of the aperture of the object-glass will then be used and nothing but actual diaphragms placed behind the object-glass, or in some other part of the microscope, will produce anything but an evenly illuminated disc aperture. The resolution of objects viewed by opaque or dark ground illumination requires no further consideration than the size of the aperture of the object-glass, as shown in Figs. 60 (*a* and *b*).

The resolution of objects viewed by transmitted light is not so simple.

Objects thus illuminated almost always scatter a certain quantity, and sometimes quite a large quantity, of light, which tends to utilise the whole aperture of the object-glass, even if this aperture is not equally illuminated by the condenser.

That they seldom do so to a sufficient extent to destroy the abnormal appearances caused by bad illumination is shown by the following experiment.

A few micrococci were placed in the field of an 8 mm. apochromatic object-glass. With a ×50 eyepiece and with full aperture they showed a clear row of dots unequally spaced (Fig. 66 *a*). A diaphragm was then placed below the condenser, which was of the shape of the aperture in Fig. 62 *k*, the apertures being parallel to the row of micrococci. This produced such bad definition that at first they were not recognised, but were finally seen to be as shown at Fig. 66 *b*, although not so black as drawn. The aperture was then turned at right angles to the row, and the dots looked like two very fine bacilli surrounded with a membrane, as shown in Fig. 66 *c*.

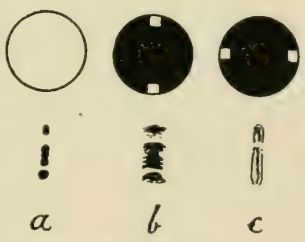


FIG. 66.

A fine transparent line in an opaque surface, such as a spirillum in an Indian ink preparation, or a minute dot or scratch in a silver film, will scatter light in all directions, as shown in Fig. 47, page 57, by diffraction. The edge of any object scatters a small amount of light. A mass of cells, as viewed in an animal or vegetable tissue, acts like a number of small lenses and reflectors and distributes light in the same manner as a cut-glass shade, but small isolated objects, such as bacteria on a bright field, do not

produce a great deal of scattered light, and the experiment described above shows that illumination in this case is of primary importance.

The special case of periodic structure, such as the markings on diatoms, or fine ruled lines, is of particular interest in this connection.

A series of parallel lines on the stage of the microscope distributes the light by diffraction, as in the case of a single slit shown in Fig. 47 ; a large fan of light will emerge from the rulings. If they are illuminated with a wide-angle cone of light the distribution tends to become equal at all angles after it has passed through the ruling, but if a parallel or almost parallel beam of light is used to illuminate them—if, for instance, the diaphragm, below the substage condenser be closed to a pinhole—this light is not distributed in an equal manner throughout the fan, a very pronounced amount of selective diffraction takes place and certain portions of the cone of light will be entirely blocked out, in a similar manner to that shown in Fig. 50. If the object-glass has an aperture large enough to just collect the first bright image between B and C, Fig. 50, and if its back lens be examined, it will be found to resemble the appearance of the aperture in Fig. 62 *j* or *k*, except that there is also a central beam. There will be one beam of light in the centre of the aperture and one on either side which, if the lines are of a particular fineness, will be at the extreme edge of the aperture. The portion of the aperture of the object-glass that is actually in use is determined by the diffraction set up by the object itself, and thus, although only a parallel beam is used to illuminate the object, the lines can be seen, because the diffracted light throws light into the lens aperture of such a shape that it produces antipoint images that assist in resolving the lines. It is a spurious resolution. It is not equal to the resolution obtained by the use of a wide-angle illuminating cone which destroys the diffraction images otherwise formed by the object, but it is a curious instance of how certain forms of periodic structure in the object, if illuminated by a beam of parallel light, have just that selective action on the shape of the aperture utilised which tends to form an image similar to the object itself.

An object-glass that has an aperture which by correct full-cone illumination will resolve a certain number of lines to the inch will, when illuminated by a direct narrow parallel beam of light, give spurious resolution of lines half as fine but no more. The spurious resolution is only half the true resolution.

To give an example. A lens of ·65 N.A., when illuminated with a full cone of light, will give resolution of 60,000 lines to the inch. If it is illuminated with parallel light the exact centre of the lens only is utilised by the direct light, but the two first diffracted beams, *a a'* Fig. 67, thrown off by lines 30,000 to the inch are just included in the aperture.

The image of a single point produced by these three beams of light acting together is a series of lines as in Fig. 62 *k*, and these lines in the image correspond in their distance apart to 30,000 to the inch in the object, and therefore give the appearance of resolution, but only half that which would be given with correct resolution. If lines finer than 30,000 to the inch are examined the first diffraction images are outside the grasp of the object-glass at *b b'* Fig, 67, and no light, except the central light at *c*, can take part in the formation of the image. There is consequently no resolution. A curious experiment may now be tried. If a small black central patch be inserted behind the object-glass to stop out the central light *c*, no lines finer than 30,000 to the inch can be resolved, but the 30,000 lines will appear to be doubled throughout and will appear to be 60,000 to the inch. It is not resolution of fine lines, but an incorrect appearance of coarse lines. This is because each point of the image is depicted as lines by an artificial aperture of the shape as in Fig. 62 *k*. They are twice as close together as when formed by an aperture in which the central light is also present.

FIG. 67.

The diatom Pleurosigma angulatum is an even more striking instance. It consists of a series of apertures or dots arranged in rows of such a nature that when illuminated by a parallel beam it emits diffracted light in such directions that the portions of the aperture of the object-glass used are as shown in Fig. 63 *m*, and the antipoint formed is as though a diaphragm of that shape were placed behind the object-glass. If such a diaphragm is actually used a picture of a single point appears as a series of seven dots, and it is easy to see how in this case a dot image of this diatom can be produced with a parallel beam of illuminating light, because of the effective aperture thus formed. Here again the resolution is spurious, and the dots can be seen properly resolved by an object-glass with a much lower aperture filled with light than one which admits the central beam and the complete ring of diffracted beams illustrated in Fig. 63 *m*. The illustrations, Fig. 64 and Fig. 65, are copies of two photographs from *The Microscope and its Revelations* by Carpenter, both of Pleurosigma angulatum. Fig. 64 is resolved with a beam of nearly parallel light, making use of an aperture in the object-glass of the type shown in Fig. 63 *m*, while Fig. 65 is resolved with a full cone of light from the substage condenser. Fig. 64 illustrates spurious resolution which gives an average pattern structure as against Fig. 65 which shows detailed characteristics.

Except in the case of certain diffraction gratings the central light is very greatly more intense than the diffracted light that passes through the other portions of the aperture, and this has an effect upon the antipoint. It is not so marked an effect as

might be expected, but the antipoint, as illustrated in Fig. 62 *n*, appears to be similar to that of 62 *m*, but somewhat faintly superimposed over the antipoint that would otherwise be produced by the central light alone. It is a combination of Figs. 60 *b* and 62 *m*, and the dot pattern appears over a hazy background without so much contrast. The antipoint theory was first developed by J. W. Gordon in his papers to the Royal Microscopical Society, in opposition to a theory attributed to Professor Abbe, in which this spurious resolution was supposed to be the key to microscopic vision.

It is only regular periodic structure in an object that produces the strongly marked selective diffraction which under suitable conditions of illumination shows certain coloured spectra at the back of the object-glass.

Such effects are not caused by irregular structure.

A great deal of attention has been directed to these coloured spectra. When they meet in the final image they are all recomposed into white light, and the only reason why they affect microscopic vision is because they alter the shape and size of the aperture that is actually employed. Their presence for this reason is almost always detrimental. The illuminating cone of light should never be so small that they are visible as a distinct diffraction pattern when the back aperture of the object-glass is examined.

The foregoing discussion has treated light as though it had a wave length of constant value, but it must be remembered that the wave lengths of light are approximately as follows :—

Red	$\frac{1}{35000}$ inch
Orange	$\frac{1}{40000}$,,
Yellow	$\frac{1}{44000}$,,
Green	$\frac{1}{50000}$,,
Blue	$\frac{1}{60000}$,,
Violet	$\frac{1}{70000}$,,

As the wave length of the violet end of the spectrum is nearly twice as short as that of the extreme red, the antipoints formed by pure violet light will be nearly twice as small as those formed by red light, and the resolution of the microscope nearly twice as great. If white light is used the most powerful component colour is yellow and the resolution obtained is what would be given by that coloured light. Violet light is a very unpleasant light to work with, and either blue or blue-green light is, in practice, the best colour to use for giving the highest resolving power.

It has been stated that when two lines or points could be just distinguished as being two elements and not one, they are said to be resolved. If brilliant lines or points seen on a dark ground were always being considered like the stars seen in the sky at night, if all lenses were perfect, and if flare and glare did not exist,

resolution might then be said to be entirely due to the size and shape of the aperture and the wave length of the light. Many objects are faint and only slightly darker than the space surrounding them. With dark ground illumination objects may reflect a large quantity of light from one portion which may obscure delicate structure in other portions, and the question of contrast introduces serious modifications; but disregarding these questions certain practical results follow from the examination of the diffraction theory.

Such trick illumination or accidental phenomena as have been referred to with reference to the display of ruled lines and diatoms may be neglected. The best resolution will be obtained, even with such structures, when a well-corrected substage condenser is used and the light is so focussed that the back lens of the object-glass is equally filled with light. The prevalent idea that an object-glass capable of resolving diatoms well may not be the best for other work is a mistaken notion gained from the extensive use of what is here called trick illumination. An average pattern of diatom structure can be obtained by this means with a bad lens, although even then a better lens will give a better image; but if a lens illuminated in such a manner that its aperture is evenly filled with light will resolve lines of a certain degree of fineness, that is a fair method of ascertaining the degree of sharpness with which it will show all other objects, always assuming that it gives the maximum contrast obtainable.

It is not impossible that some particular shape of aperture may be found that will give a smaller antipoint, but in general we may state that the using of the whole aperture of the lens evenly filled with light will always give the best resolution; and if in order to increase contrast or to reduce glare the aperture of the illumination must be reduced, it is at the expense of resolution.

There may be cases where special diaphragms in the condenser will indicate the presence of structure which would otherwise be undetected, but the results so obtained may be misleading and can only be correctly interpreted by a careful study of the antipoint that such a method of illumination forms.

It is easy to examine the antipoints formed by brilliant points of light on a dark background. The antipoints formed by black dots on a white ground are almost impossible to observe, as the fainter parts of the pattern are indistinguishable against the white background, though they follow the same laws; and Fig. 66 is a good illustration of the erroneous impressions that may be formed from badly illuminated objects. Fig. 66 *c* looks as though it were a short bacillus surrounded by a membrane, whereas its true structure is a row of black dots.

Microscope object-glasses of low and moderate powers are almost always made to give a higher degree of resolution than is

required when moderate-power eyepieces are used, but it is with the highest powers where the limit of resolution has been reached that these questions become of paramount importance. The aperture of a high-power object-glass is much too small for the magnifying power that could otherwise be used with advantage.

The use of monochromatic blue-green light, which shortens the wave length, is of great advantage, although with certain classes of stained specimens where colour differentiates the structure it is inadmissible. Photography will, if the correct plates are used, give still further resolution, but the ordinary gelatine emulsion, which has its maximum sensitively near the green portion of the spectrum, gives little increase. Plates must be selected which are specially sensitive to violet or ultra violet light.

High-power microscopic vision depends essentially upon resolution, but other factors come into play that sometimes make it advisable to so illuminate the object that the full aperture of the lens is not used, and the full resolution is not obtained; for instance, a small almost transparent body may be rendered invisible by illuminating it with a full solid cone of light from the condenser, and it may be necessary to use a small angle of light to render it visible, an imperfect image being better than none at all. Glare and reflections frequently throw a cloud of mist over a picture which obliterates fine detail, and to reduce this it may be necessary to sacrifice some resolution and reduce the angle of the illumination. The questions of contrast in light and shade or in colour or the imperfection of the corrections of the different zones of a particular object-glass are modifying factors, but microscopic images will always be more nearly correct representations of the objects they portray when full resolution can be obtained.

The explanation of the theory of microscopic resolution has been discussed purely with reference to the image formation of a point, assuming that any object can be divided into a mass of small points, and that if the image of each point is a perfect image, a perfect image of the whole object will be obtained. The discussion assumes that a very minute point, however it is illuminated, will give out light that emerges in one phase; that even though light may fall upon it in many different phases, when it passes through a single point it may be supposed to have acted upon a single particle of ether and to have reached one resultant phase when it emerges. This appears to be a reasonable assumption and corresponds with practice. It is difficult to see how the diffraction images shown on pages 73 to 76 could be produced unless such was the case; no change in illumination appears to make any marked alteration in the patterns.

As regards any interference effects that may be caused be-

tween adjacent points in the image no definite conclusions can be predicted unless the difference in phase between the light from such adjacent points is known or assumed. It is probably very seldom that any definite constant difference exists, and there is no evidence at present that such interference has any important bearing on microscopic resolution.

CHAPTER IV

THE PHOTOMETRY OF THE MICROSCOPE

Loss of light due to magnification—Illumination dependent on square of distance of source—Light-gathering power of microscope due to aperture—Photometric values of standard object-glasses—Aperture partially compensates for loss due to magnification—Relative brightness of object and image with different apertures and powers—Area of eyepoint a measure of brightness—Method of calculating photographic exposures—Photometry of a bull's eye—Photometry of a ring illuminator—Illumination of vertical illuminators—Opaque and transparent illumination compared—Photometry of substage condenser—Brightness with high-power dark ground illuminator—Comfortable degrees of illumination.

An object that may appear brilliant to the naked eye, when it is placed on the stage of the microscope and viewed under quite a moderate magnifying power will often look dim, and sometimes be almost invisible, and the illumination requires to be increased for it to be clearly seen. The total light which the object emits is spread over a larger area in the image, due to the magnified image being larger than the object, therefore there is less intensity at any individual spot. The area of an image is the square of its length or breadth,and it is by the relative length of the object, compared with its image, and not its area, that the magnifying power is determined, therefore the illumination will vary according to the square of the magnification. A square floor of tiles that is three times the length of another similar floor has nine times as many tiles. A microscope that magnifies an object 20 diameters, magnifies the area 400 times, and requires the light to be 400 times as bright in order that the image should be as brilliant as the original object.

Objects examined under the microscope may be transparent and be viewed by light thrown through them, or they may be opaque and be viewed by light thrown upon them. In order to see the pattern of a piece of lace by looking through it, a feeble light only is required, but in order to examine the stitches by light thrown upon it and reflected back, a strong illumination is necessary. Thus, although Photometry, or the measurement of the brilliancy of light, is not often actually attempted in microscopic work, the conditions of microscopic vision require such different degrees of illumination for different classes of investigation, that some slight acquaintance with the laws of Photometry is desirable.

If a small source of light is radiating light in all directions the amount that falls upon any particular spot will depend upon the square of its distance from the source of light, for suppose a point source of light exists at A, Fig. 68, and that it is supposed to be enclosed within a sphere B D C E, the whole of the light that is given out by the source A is spread out over the sphere, and the brilliancy at any point on the sphere will be equal to the total light given out at A, which may be called i, divided by the area of the sphere. The area of a sphere is $4\ \pi\ r^2$ where r is the radius of the sphere. Therefore, the brilliancy at any point on the sphere will be

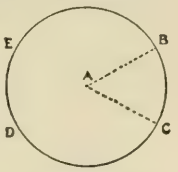


FIG. 68.

$$\frac{i}{4\ \pi\ r^2};$$

or if we call $\frac{i}{4\ \pi} = \mathrm{K}$ it will be $\frac{\mathrm{K}}{r^2}$,

and the total light received by an area of size B C^2 will be

$$\mathrm{K}\ \frac{\mathrm{B}\ \mathrm{C}^2}{r^2}.$$

That is to say, it is proportional to r^2, or the square of the distance of the source of light.

If the source of light is not a point but a small area of a definite size, say S^2, then, as each point of this area will behave in a similar manner, the brilliancy will be

$$\mathrm{S}^2\ \mathrm{K}\ \frac{1}{r^2}$$

and the total light received by an area B C^2 will be

$$\mathrm{S}^2\ \mathrm{K}\ \frac{\mathrm{B}\ \mathrm{C}^2}{r^2}.$$

To take an example; suppose a lamp is of such an intensity and size that it is giving out the amount of light that would be given out by ten standard candles, then the brilliancy S^2 K will be 10 candle-power; and if the sphere has a radius of 1 foot, then the illumination at a distance of 1 foot from the lamp will be 10 foot-candles.

If the distance (r) is 4 feet, that illumination will be $\frac{10}{r^2} = \frac{10}{16} = \frac{5}{8}$ foot-candle.

By this means, if the candle-power of an illuminating source and its distance from an object are given, the brilliancy of the illumination, or the intensity of the light that falls upon the object, is obtained by dividing the candle-power by the square of its distance from the light.

The amount of light that reaches the object and the amount that enters the microscope may be very different. If the object is semi-transparent and the light passes through it, the brilliancy of the light that enters the microscope may be almost the same as that of the illumination on the object; but if the object is opaque and only reflects the light, it may be only a very small proportion that enters the instrument. It will depend on how large a proportion of the light received is reflected into the aperture of the object-glass. A white object may reflect most of the light that it receives, while a dark one may only reflect 5 per cent.

But suppose the object be such that it reflects the whole of the light that falls upon it. It usually does not reflect it in one direction only, but scatters it in every direction over the area of a hemisphere equal to a solid angle of 180°, and the amount which is thrown off in any particular direction is but a small fraction of the illumination which the object receives.

If the object is examined by the microscope the proportion received by the microscope will depend on the aperture of the object-glass.

If A, Fig. 69, is a point on the illuminated object, and if the object-glass can collect an angle of light from each point of the object equal to the cone C A D, then the percentage of light that will pass into the microscope will depend on the area of that portion of the surface of the sphere which is limited by a circle with a diameter of C D compared with the area of the surface of half the sphere.

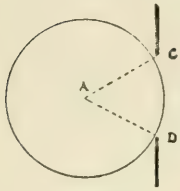


FIG. 69.

The following table gives the approximate percentage of the total light scattered by an opaque object that can be received by object-glasses of different numerical apertures.

N.A.	Angle.	Percentage of total scattered light that is collected.
·1″ . . .	11°	½
·2″ . . .	23°	2
·3″ . . .	35°	4½
·4″ . . .	47°	8¼
·5″ . . .	60°	13
·6″ . . .	74°	20
·7″ . . .	89°	29
·8″ . . .	106°	40
·9″ . . .	128°	56
·95″ . .	143°	68
1·00″ . .	180°	100

The table assumes that the light entering the microscope from an opaque object is scattered equally in all directions.

The table also gives the same information as regards transparent objects viewed with transmitted light, provided the whole aperture of the object-glass is filled with light equally distributed; but in many cases, when transmitted light is used, the whole aperture of the object-glass is not used: the mirror or the substage condenser may be directing too narrow-angled a beam of light to fill the aperture (see page 116); and in this case the photometric value of the light must be obtained from that portion of the aperture of the object-glass which is filled with light and not from the maximum aperture. With opaque objects which radiate light in all directions the whole aperture of the object-glass is always filled with light.

From the foregoing remarks it will be seen that it is possible from a set of tables to estimate the amount of light that is thrown into a microscope object-glass when transmitted light is used, but that in the case of opaque objects or objects illuminated with dark ground illumination, no very definite figures can be arrived at, as different objects behave so differently as regards the amount of light which they reflect.

It will, however, be noticed from the foregoing table that as the numerical aperture of an object-glass is increased so its light-gathering property is also increased.

The standard series of object-glasses gather light in somewhat the following ratios:

Focal length.	N.A.	Relative light-gathering property.
1½″ 32 mm. . .	·15	1
⅔″ 16 „ . .	·28	4
⅓″ 8 „ . .	·5	12
⅙″ 4 „ . .	·85	44

It might, therefore, be supposed that the 1/6th″ gives a more brilliant image than the 1½″; if the whole aperture is used it receives 44 times as much light; but this is modified by the magnifying power. The 1/6th″ magnifies the object eleven times as much as the 1½″, and the magnifying power is reckoned by the length of the object and not by its area. The image of the object produced by a 1/6th″ is eleven times as long as the image produced by the 1½″, but has $11^2 = 121$ times the area, and therefore the light must be 121 times as powerful to give the same brilliancy at any point. The larger aperture of the 1/6th″ helps to make up for the loss of light due to magnification, but only partially overcomes

the loss, and the actual illumination with the 1/6th″ will be $\frac{44}{121}$, or about $\frac{4}{10}$, that of the $1\frac{1}{2}$″.

A formula can be obtained that will express the relative brilliancy of the appearance of the image compared with that of the object.

An observer who examines an object at 10 inches distance (250 mm.) receives from each point of that object a cone of light represented by a solid cone of which the diameter of the base is equal to the diameter of the pupil of his eye. It is true that the pupil varies in size according to the brilliancy of the light. It also varies with different individuals; but for purposes of microscopic work it may be assumed that the light is sufficiently bright to reduce the diameter of the pupil to a small size which may be taken to be $2\frac{1}{2}$ mm. in diameter.

The angular size, therefore, may be assumed to be $\frac{2{\cdot}5}{250} = \frac{1}{100}$, or to express it as a numerical aperture ·005 N.A., and the relative amount of light collected by a microscope as compared with the eye, in proportion to the square of the numerical apertures of the microscope to that of the eye, will be $\frac{\text{N.A.}^2}{(005)^2}$[1]; and to obtain the brightness of any point in the image, this must be divided by the square of the magnifying power. The brilliancy of the image will, therefore, be the apparent brilliancy of the object multiplied by

$$\left(\frac{\text{N.A.}}{(\cdot 005)\ \text{M}}\right)^2.$$

Suppose a microscope with a total magnifying power of 100 has an object-glass with a numerical aperture of ·5 N.A. The illumination of the object-glass will be

$$\left(\frac{(\cdot 5)}{(\cdot 005)\ (100)}\right)^2 = 1;$$

or is of the same brilliancy as the object appears to the eye at 10 inches. That is to say, to produce equal brilliancy the object-glasses should have a particular N.A. for each magnifying power, whether produced by the eyepiece or the object-glass or the tube length.

The following table gives the N.A. required for different magnifications. As the microscope absorbs about 50 per cent. of the

[1] This is not strictly accurate, as the area of the spherical cap, and not the area of the disc, should be considered, and the figures in the table on page 91 must be taken only as an illustration.

light, then values for N.A. should be doubled to give the actual N.A. required.

—	Theoretical.	Actual.
50 . .	·25 N.A.	·5 N.A.
100 . .	·5 N.A.	1 N.A.
200 . .	1 N.A.	2 N.A.
500 . .	2·5 N.A.	5 N.A.
1,000 . .	5 N.A.	10 N.A.
2,000 . .	10 N.A.	20 N.A.

In cases where the illumination is feeble the pupil of the eye expands to two or even three times the diameter which has been taken as a standard, and to obtain with the microscope equal illumination for feeble lights the numerical aperture would require to be four or even nine times greater than the figures given. The numerical apertures required to give equal illumination are never obtained in practice, and therefore the image seen through a microscope is never as bright as the object itself.

A more useful table is given below of the relative illumination of the image, shown as a percentage of the illumination of a transparent object applied to standard object-glasses. The table might have been made up giving nothing but magnifying powers and apertures, as the object-glass used or the method of obtaining the magnifying power, whether by a high-power eyepiece and a low-power object-glass, or vice versa, does not affect the result.

It is assumed that the instrument transmits 50 per cent. of the light received.

Object-glass.	Numerical Aperture.	Magnifying powers and the percentage light compared with the appearance of the object as seen by the naked eye.					
		Mag. power.	Brightness.	Mag. power.	Brightness.	Mag. power.	Brightness.
40 mm. .	·16	25	*50%	50	20%	100	6%
32 ,, .	·15	25	*50%	50	18%	75	8%
16 ,, .	·28	60	43%	100	16%	150	7½%
16 ,, .	·35	60	*50%	100	24%	250	4%
8 ,, .	·5	120	35%	200	12½%	300	5½%
8 ,, .	·65	120	*50%	200	21%	500	3½%
4 ,, .	·85	300	16%	400	9%	600	4%
38 ,, .	·95	400	11½%	600	5%	1,000	2%
38 ,, .	1·2	400	18%	600	8%	1,500	1½%
2 ,, .	1·3	600	9½%	1,000	3½%	2,000	¾%

This table assumes that the pupil of the eye is 2½ mm. diameter; it shows that with a 40 mm. object-glass used at a magnifying

power of 50 the image seen through the microscope will have 20% or $\frac{1}{5}$ of the brilliancy of the object viewed by the naked eye.

NOTE.—The figures marked * would be 82%, 72%, 63%, and 57% respectively if the pupil of the eye were larger: the diameter of the pupil reduces the effective diameter of the eyepoint.

The above results may also be obtained from the size of the eyepoint, which is convenient because, if the whole of the aperture of the object-glass is not being used, this method indicates the actual light received by the eye.

If the diameter of the eyepoint is the same as the pupil of the eye then the illumination of the image will theoretically be the same as the illumination of the object (in practice due to absorption and reflections, say about $\frac{1}{2}$), and the diameter of the eyepoint is $2\,Z = \frac{2\,N.A.250}{M}$ (see page 32).

Thus if the magnifying power is 100 and the N.A. ·5, then $2Z = 2{\cdot}5$ mm., which is the assumed diameter of the pupil of the eye; and the relative illumination between image and object is obtained by dividing the diameter of the eyepoint squared $(2Z)^2$ by the diameter of the pupil of the eye squared. It is assumed that the light is equally distributed in the eyepoint, which is not always the case.

The table also shows that high-power lenses require more powerful illumination than those of low power, and it becomes interesting to examine the various means of increasing the brilliancy of illumination which are employed; but before doing so some deductions may be made which are useful for determining correct exposures in Photomicrography. It follows from the above considerations that, with a given source of light and a fixed loss of light due to absorption and reflection of the lenses, the intensity of the eyepoint per unit area is always the same whatever the magnifying power or aperture of the microscope. The exposure, therefore, that is required on a photographic plate placed at any given distance from the eyepoint is dependent only on the area of the eyepoint or the square of its diameter. The larger the eyepoint the less the exposure that is required. The correct exposure also varies according to the square of the distance of the photographic plate from the eyepoint. To give an example: suppose the correct exposure is ascertained when the plate is 10 inches from an eyepoint of 2 mm. diameter. If the eyepoint is reduced to 1 mm., either by a change of the eyepiece or object-glass, or by reducing the cone of illuminating light, the exposure will require to be increased four times. If the plate is 20 inches from the eyepoint instead of 10 inches the exposure would require again to be increased by four times.

The exposure of photographs is, however, very dependent on

the absorption of light which takes place in different types of lenses—there is so great a divergence in the number and shape of the surfaces employed that the above rule, which is accurate provided the same lens is used, requires some modification with different lenses.

The most common method of increasing illumination is by means of a convex lens. A bull's eye is the term generally employed to represent a strongly convex lens used for the purpose of condensing light to a focus or for collecting it from a point source and rendering it parallel. It may be flat on one side and curved on the other; or it may be convex on both sides. The term is only applied to a lens that is powerful compared to its size, and its curves are, therefore, strongly convex. Those used with the microscope are generally between $2\frac{1}{2}$ and $3\frac{1}{2}$ inches in focal length, and of a diameter only slightly less than their focal length.

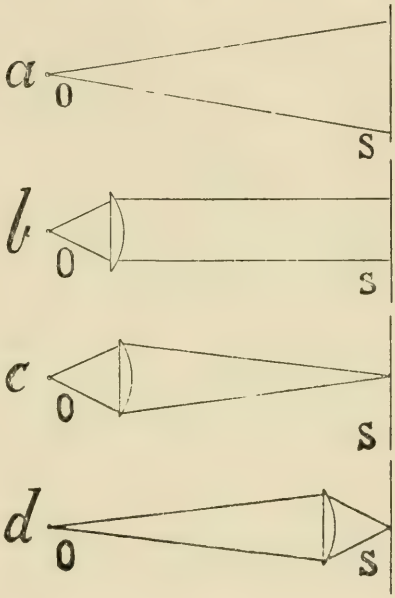


Fig. 70.

The method by which they concentrate light upon an object cannot be properly understood as explained by an ordinary optical textbook diagram which illustrates the passage of light through a lens. Such diagrams almost always show the light as a point and illustrate what happens to the light that emerges from that point as it passes through the lens, but a light, except in the case of a distant star, is never a point but an area of a definite and often a considerable size. Therefore, before considering the photometry of a bull's eye it is well to look at the matter from a different point of view.

Fig. 70 shows the ordinary textbook illustrations in which O is a point source of light and S is a screen illuminated by the light at *a* without a bull's eye, at *b* where the bull's eye is so placed as to give out so-called parallel light, at *c* so as to focus to a point on the screen, and at *d* so as to focus the light to the screen in the second position, where a lens can be placed to accomplish this. Such diagrams are misleading. It would appear

that the condition at *c* would produce most light, because as compared with *d* it collects a larger angle of light from the source and brings it all to a point on a screen; but this is not correct.

To obtain a true idea the size of the source of light must be considered; and if a new set of diagrams are drawn in which not only the light from the central point but that from a point at each extreme edge of the source is shown, the size of the picture of the source of light which is thrown upon the screen will enable a more complete idea to be obtained of what is happening.

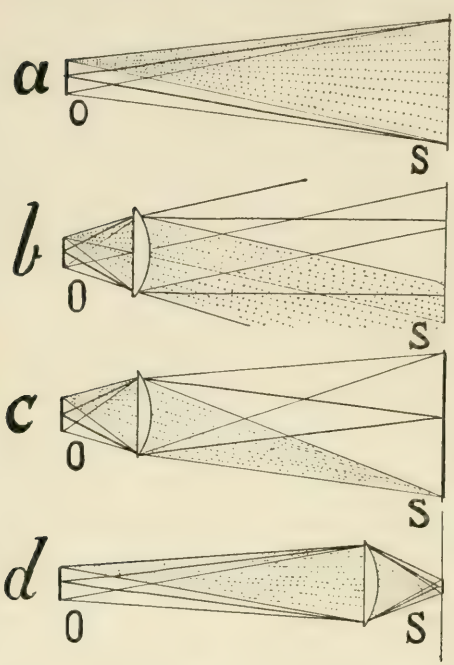


FIG. 71.

The so-called parallel light emitted by a condenser, when the light is in its focus, as shown in Fig. 71 *b*, is far from being a parallel beam when the light source possesses any size, and when it meets the screen it is spread over a large area. In the cases *c* and *d*, where the light is focussed to form an image of the source, the size of the image is much larger in the case of *c* than in that of *d*, and the light received from the source by the bull's eye is spread out in the case of *c* upon a much larger area than the source, and in the case of *d* upon an area smaller than the source. So that although the lens in the case *c* collects more light, it spreads it over so much larger area that investigation will show that the position of the bull's eye at *d* will give the most intense illumination on the screen.

In the case of Fig. 71 *a* the brilliancy of the light received by an object illuminated by a source of light with an area S^2 will be

$$S^2 K \frac{1}{r^2}. \qquad (1)$$

Interpose a lens, as in Fig. 71 *c* or *d*, and the light received by the bull's eye will be

$$S^2 K \frac{L^2}{x^2} \qquad (2)$$

where L^2 is the area of the bull's eye and x its distance from the source of light. The whole of this light, disregarding the small percentage absorbed or reflected by the lens, will be transferred to the screen S, but it will be distributed over an area according to the size of the image of the source which the lens produces. The relative size of the source of light and its image is in the ratio x, the distance of the lens from the source and x' the distance of the lens from the screen; therefore, the intensity of the light at any point on the screen is

$$S^2 K \frac{L^2}{x^2} \div \frac{S^2 x'^2}{x^2} = K \frac{L^2}{x'^2}. \qquad (3)$$

To take an example:

If S = 10 millimetres $S^2 = 100$ sq. mm.
$r = 400$ millimetres $r^2 = 160{,}000$ mm.

Then the illumination by an object from the source of light without the use of a bull's eye, is

$$\frac{K\,100}{160{,}000} = \frac{K}{1{,}600} \text{ per unit area;}$$

and this forms a basis for comparison as being the light received when no bull's eye is used.

If a lens has a focal length $f = 75$ mm. and a diameter of

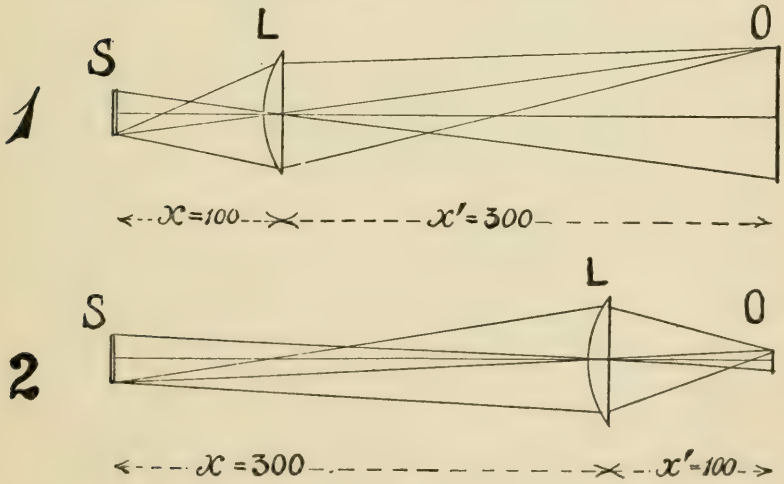


FIG. 72.

58 mm. and if circular an area $L^2 = 2{,}642$ mm: at 100 mm. from the source of light it will produce an image of that source at a distance of 300 mm. from it. The two conjugate focal distances being $f + \frac{1}{3}f$ and $f + 3f$, and the magnifying power being three. Or it may be placed 300 mm. from the source of light and it will produce an image of the source at a distance of 100 mm., the magnifying power being one-third.

Fig. 72 (1) shows the bull's eye at a distance $x = 100$ from source $x' = 300$. Fig. 72 (2) shows a bull's eye at a distance $x = 300$ from source. The axis of each bundle of light passes through the centre of the lens, and thus from similar triangles; the relative diameter of the source and its image are in Fig. 72 (1) 1 to 3, and Fig. 72 (2) 1 to $\frac{1}{3}$.

These are the two positions, namely when the lens is at 100 mm. and 300 mm. from the source of light, where images can be formed in the given total distance of 400 mm. by a lens of 75 mm. focal length.

By inserting the values in the equation (3) the intensity of the light on the screen is

for case C Fig. 71 $\quad K\dfrac{L^2}{x'^2} = \dfrac{K\,2{,}642}{90{,}000} = \dfrac{K}{32}$;

for case D Fig 71 $\quad K\dfrac{L^2}{x'^2} = \dfrac{K\,2{,}642}{10{,}000} = \dfrac{K}{3{\cdot}8}$.

The relative intensities are, therefore,

(*a*) No bull's eye $\dfrac{1}{1{,}600}$

(*b*) Bull's eye near source of light $\dfrac{1}{32}$, an increase of 50 times.

(*c*) Bull's eye near screen $\dfrac{1}{3{\cdot}8}$, an increase of 420 times.

This indicates how the use of a lens or bull's eye condenser, placed in such a manner that it focusses an image of the light source upon an opaque object, increases the intensity of the illumination and gives the extra light required for microscopic examination. If an object is sufficiently well illuminated by the light without a bull's eye to be clearly seen by the naked eye, then in the example given above the use of a bull's eye in the manner described, as *c* Fig. 71, would enable the object to be seen with the same brilliancy, using a microscope having a magnifying power of 7 diameters, because the area of the image formed by a microscope magnifying seven diameters will be forty-nine times the area of the object and the light is fifty times as brilliant.

Similarly, the use of a bull's eye in the manner described, as *d* Fig. 71, will admit of the use of a magnifying power of twenty diameters without reduction in brilliancy.

Another method of condensing light upon opaque objects is by means of a reflector or a portion of a reflector fitted on the object-glass of the microscope, the light being thrown upon the reflector by the ordinary mirror of the microscope as shown in the diagram, Fig. 73. This method was first suggested by Lieberkuhn, and such illuminators were called by his name, but they were made of silvered metal and of a single spherical surface. The aberrations of a spherical reflector are so great and the difficulty of keeping a metal reflector brilliant are such that the concentration of the light was not sufficient, and they have gone out of general use.

Recently, however, a modified form has been patented by Messrs. Beck (Fig. 73), in which, by the use of a glass ring with special curves, the aberration of the ring has been corrected and the silvering at the back surface renders the polish permanent. By the shape of the curves the size of the ring has been so increased over that of the original high-power Lieberkuhn that these Aplanatic Ring Illuminators can be used with object-glasses as high in power as 4 mm. (1/6th inch).

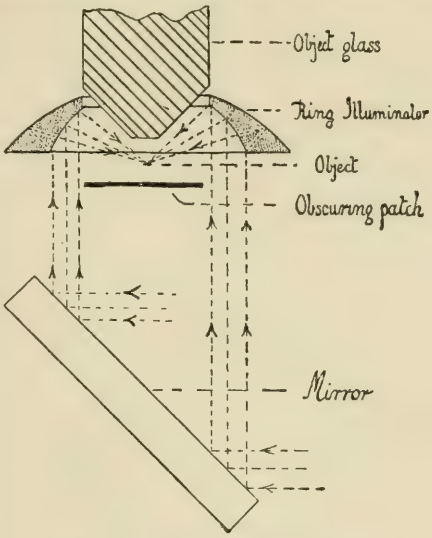


FIG. 73.—Beck's Aplanatic Ring Illuminator.

The increase in brilliancy follows the same laws as that of the bull's eye, and is given by the formula 3, page 95. The focal length of these reflectors is so short compared with their area that the increase in illumination is unexpectedly great. For example, the photometric brilliancy of that made for the object-glasses up to 8 mm. focus is as follows :

Area of ring $L^2 = 370$ mm.
Focal length approximately equal to $x^1 = \cdot 11$ mm.
Intensity = 3K, an increase of 4,800 times of an object illuminated by a light placed 400 millimetres from the object (see page 96).

The intensity of a similar reflector for use with a 4 mm. object-glass (·85 N.A.) is about 2,800.

In the case of illumination by means of a thin glass or vertical

illuminator used over the object-glass and throwing light down upon the object, the object-glass may be considered as a bull's eye of short focal length, and the same formula, 3, page 95, gives the increase in brilliancy due to the object-glass; but in this case the illumination is influenced by other factors. A transparent thin glass reflector will transmit a beam of light as large as the full aperture of the object-glass if it is not limited by diaphragms, but it will only reflect about 6 per cent. of the light which is thrown upon it. A prism reflector will only transmit a beam half the area of the object-glass, and this will again be reduced to half as it returns through the instrument to the eye; on the other hand, it will reflect about 80 per cent. of the light which is thrown upon it.

The loss of light by reflection at surfaces and absorption of lenses has not been alluded to. Every glass-to-air surface gives rise to a loss of about 4 per cent., and a small quantity is lost by absorption. In the case of a bull's eye, a loss of not less than 10 per cent. takes place, but in the case of light from a vertical illuminator thrown down through an object which may have ten or more surfaces, a much greater loss of light occurs.

The actual loss of light in the latter case is not a serious disadvantage, but the direction in which it is reflected is such that unless special precautions are taken it enters the eye and causes glare. The Ring Illuminator does not cause any glare, and is now coming into use for metallurgical and other work for this reason.

These photometric considerations have so far been applied to the illumination of opaque objects. Their application to objects viewed by transmitted light is not quite so simple. If an opaque object receives light from any direction, or from several directions at once, its brilliancy is increased, and except for shadows caused when the object has a rough surface, the light received from any direction or from any source will be reflected or scattered in all directions, and it is no matter where or how the light gets to the object. The same holds good with objects observed by the naked eye, but the examination of objects by transmitted light is not the same.

Judged by the experience of everyday life it is unnatural to examine objects by transmitted light. The pattern of a fabric, the water-mark on paper, or a photographic negative may be examined by holding it between the sky and the observer's eye, but such cases are exceptional. So many objects examined by the microscope, however, are transparent that this unnatural method is the most frequent form of illumination employed.

If in Fig. 74 a beam of light, E C, illuminates an opaque object, this will be reflected back in all directions, and a proportion will enter the eye in the direction O A B. Any other illuminating beam, as F D, will also be scattered by the object and a similar

proportion, O A B, will be received by the eye, and so on, for all light that falls upon the object; but if an object be examined by the eye by transmitted light, as in Fig. 75, the only light that passes through the object that can enter the eye is the bundle A O B, and any further light that can be thrown upon the object at a greater angle, as from C to D or from E to F, will not enter the eye and will not increase the illumination.

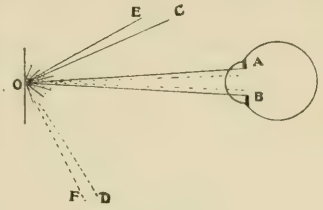


FIG. 74.

In ordinary vision, the pupil of the eye limits the cone that can enter the eye, and the diameter of the pupil, compared with the distance of the object from the eye, forms the numerical aperture of the unassisted eye. The aperture of the microscope object-glass limits the cone of light that enters the microscope.

Where transparent objects are examined by the microscope the maximum light can only be obtained when the whole aperture of the object-glass is filled with light.

If two object-glasses are compared, one of which has double the aperture of the other, and if the beam of illuminating light is in both cases so small that it does not fill the aperture of either object-glass, no more direct light enters one than the other unless the object itself scatters the light, due to reflection, refraction, or diffraction. A lens placed below the object increases the angle at which the light passes through the object, and serves to utilise the whole aperture of a wide-angled object-glass; and for this reason a substage condenser is necessary for use for high-power lenses, in order to make use of their large aperture.

FIG. 75.

A substage condenser may be considered in the same manner as a bull's eye for photometric purposes. Its action is merely that of a lens of very short focal length. The intensity of its illumination is obtained from equation 3, page 95, and is

$$K \frac{L^2}{x'^2},$$

where x' may be taken as the focal length and $\frac{L}{x'}$ as its aperture (2 N.A.). When the whole aperture of the object-glass is filled with light by means of a substage condenser, the aperture of the object-glass becomes the measure of the maximum illumination

that such a condenser can give as regards direct light, and the intensity becomes K (2 N.A.)^2.

From this it will be seen that the focal length of the substage condenser has no effect upon the intensity of the light, but merely is a means of filling the aperture of the object-glass.

The use of a bull's eye in combination with a substage condenser does not increase the intensity of the illumination. This may be shown by an example.

Let the substage condenser have a focal length of 8 mm., and let the light source be as before, 400 mm. from the object, and assume that the aperture of the object-glass is ·5 N.A. and that the substage condenser has a larger aperture, but that ·5 N.A. is the actual angle utilised, this aperture measures 8 mm. and has an area of 50·26 mm. The distance x' will not be exactly the focal length of the object-glass, because the light source is not at an infinite distance, but 400 mm. away, and $x' = 8{\cdot}16$. The intensity of the illumination, therefore, becomes

$$\frac{K \times 50{\cdot}26}{(8{\cdot}16)^2} = \frac{K}{1{\cdot}3}$$

Now interpose a bull's eye, 75 mm. focal length, 58 mm. diameter, in the path of the rays, so that it is 75 mm. from the source of light, and the rays from each point emerge parallel.

The bull's eye may direct beams of parallel light upon the substage condenser which are 58 mm. diameter, but only beams of light 8 mm. diameter will pass through the substage condenser; therefore, the bull's eye is only employing an aperture of 8 mm. and the useful light received by the bull's eye will be

$$\frac{K\ S^2\ L'^2}{x^2}.$$

The whole of this light is passed through the object spread out over an area which is the size of the image of the source of light. The area of this image is $\frac{S^2\ x'^2}{x^2}$ and the intensity of unit area will be as before

$$\frac{K\ S^2\ L'^2}{x^2} \div \frac{S^2\ x'^2}{x^2} = \frac{K\ L'^2}{x'^2} = \frac{K\ 50{\cdot}26}{8^2} = \frac{K}{1{\cdot}27}.$$

The effect of using a bull's eye with a substage condenser has thus only increased the intensity in the ratio of $(8)^2$ to $(8{\cdot}16)^2$, due to the slight alteration in the focus of the substage condenser caused by using parallel light instead of light coming from a distance of 392 mm. Expressed algebraically the increase in illumination may be expressed by $\frac{x'^2}{f^2} = 1{\cdot}0409$ where f is the focal length of the substage condenser. What has actually taken place, due to the use of a bull's eye, is that the size of the area of the object

which is illuminated is larger without any loss of illumination. The relative diameters of the images of the source of light, being approximately in the ratio of the focal length of the bull's eye to the distance of the light from the condenser, are in this case 75 to 392. With the bull's eye the image of this area of light is approximately five times the diameter that it is when the light is used direct.

It has been assumed that an uncorrected lens produces a perfect image, and that it distributes light equally. This is far from being the case. In the illumination of opaque objects it is not a serious matter, because, no matter where the light comes from, it will increase its brilliancy, although a certain amount may be wasted by being directed upon portions of the object which are not being examined. In the illumination of transparent objects it is a much more important question, because if the aperture of the object-glass is not equally filled with light serious errors in definition are produced, which are described in the chapter on Resolution. For this reason the best substage condensers are very accurately corrected, and produce images almost as good as microscope object-glasses, and a bull's eye should not generally be used with such substage condensers. It does not increase the illumination and only spoils the corrections of the substage condenser. So-called Aplanatic Bull's Eye condensers are only aplanatic for a portion of their aperture in the centre, and are calculated from formulæ which are only correct for a few degrees of angle.

On applying this theory to the modern form of dark ground high-power illuminator, it does not agree with practice.

The dark ground illuminator referred to is of the type with two reflecting concentric surfaces. It forms a thoroughly good image of the illuminant, it has a focal length of about ·12 inch, and is almost free from aberration; and there is no theoretical reason why it should not behave as any other well-corrected condenser, but in practice it is found that it gives a far more intense light with a bull's eye than when it is used alone.

The following experiments show that the difference is a matter of importance.

A photometric eyepiece was used in which the field of view was divided into two halves. In one the object on the stage of the microscope was seen; in the other a reflector gave a view of a screen, the brightness of which could be varied by altering the distance of a small electric light.

Experiment 1.—A piece of paper placed in immersion contact with cedar-wood oil.

(*a*) With dark ground illuminator alone gave an intensity 1.

(*b*) With dark ground illuminator and bull's eye focussed to give parallel light, intensity 3·45.

(*c*) With dark ground illuminator and bull's eye focussed to form image $2\frac{1}{2}$ inches from illuminator, intensity 15.

Experiment 2.—A specimen of Coscinodiscus mounted in an aqueous solution.

(*a*) With dark ground illuminator alone, intensity 1.

(*b*) With dark ground illuminator and bull's eye focussed to give parallel light, intensity 3.

(*c*) With dark ground illuminator and bull's eye focussed to give image $2\frac{1}{2}$ inches from illuminator, intensity 7.

Although the exactness of these figures is not to be relied upon, they are sufficient to show that the increase in intensity is very marked and requires explanation.

It was first investigated as to whether this illuminator delivered a larger angular cone upon the object under the different conditions. The focal length of the illuminator was so short that even when the image of the light was focussed by the bull's eye to a distance only $2\frac{1}{2}$ inches from the illuminator, this image was still about thirty times the focal distance away, and the light from it was not so far from being parallel compared with the reflecting power of the curves, and it should not seriously affect the optical effect of the apparatus. Careful measurement showed no appreciable increase in the cone of light delivered upon the subject.

The nature of the image of the illuminant formed by this illuminator was examined to see whether it gave any serious distortion, but it was found that it did not do so.

The question as to whether such an increase in light could be occasioned by reflection from surfaces of the slide cover-glass, object-glass, or the object itself, seemed improbable on account of the large amount of such an increase, but the following experiments show conclusively that such is the case.

Experiment 3.—An isolated malaria parasite, which filled a red corpuscle, stained and mounted in balsam, was illuminated by a dark ground illuminator and the light intensity reduced by means of a pair of neutral glass wedges, until it was only just visible. The use of a bull's eye, exactly as in Experiments 1 and 2, did not render it more visible.

Experiment 4.—A stained anthrax bacillus, mounted in balsam, gave the same result.

Experiment 5.—A specimen of stained blood mounted in balsam, viewed with a low power and put slightly out of focus so as to give a uniform matt surface of light, also gave the same result as Experiment 3.

Experiment 6.—A stained section of tissue, mounted in balsam, gave an appreciable increase in brilliancy when the bull's eye was used, but not as great as in Experiment 1 or 2.

It appeared, therefore, that specimens mounted in balsam, where the refraction is almost the same as the cover-glass and slip, are not increased in brilliancy when a bull's eye is used, and

that such increase must be due to reflection between the cover-glass and slip.

That this may be so, may be illustrated by the following diagram.

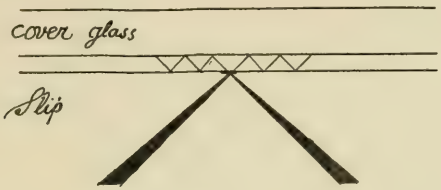


Fig. 76.

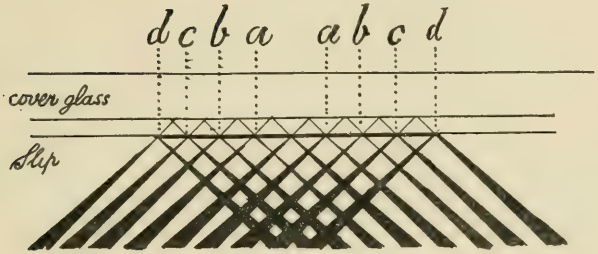


Fig. 77.

If, as in Fig. 76, the image formed by the illuminator of the source of light is very small, such light as is reflected by the cover-glass does not come back to the object and increase its brilliancy, but if in Fig. 77 the image formed by the illuminator is large, then all light from distances *a*, *b*, and *c* from the centre will be partially reflected by the cover-glass in such a manner that they fall upon the object in the centre. The effect of a bull's eye is to produce a large instead of a small image of source of light on the object, and it would appear that this is the reason for the increase in light observed on such specimens as living bacteria in water by the use of a bull's eye. The film is very thin, and many sets of reflections, as indicated in Fig. 77, take place.

If an object such as paper or even a section of tissue is of itself a reflecting material, each particle that is illuminated reflects light in all directions, and it is easy to understand that the larger the amount of the material that is illuminated, the greater will be the brilliancy of any individual point.

The foregoing remarks on the Photometry of the Microscope lead to certain practical results, which are somewhat indefinite because of the great variety of the conditions under which the microscope is used.

It is laid down by illuminating engineers that for comfortable work the following intensities of light are desirable :

Work at a desk, reading, or writing . . .	3 candle feet
Sewing light materials	4 „ „
Sewing dark materials	6 „ „
Fine engraving	10 „ „

For microscopic examination of transparent objects from 5 to 15 candle feet are required in the image, and taking an average of 8 candle feet as being a satisfactory illumination in the image, the illumination of the object, if the object-glass has a reasonable aperture, should be about

Mag. power.	Candle-feet.
50	16
100	20
300	50
600	80
1,000	250
2,000	1,050

If the whole aperture of the microscope object-glass is not filled with light four times the above figures may be required.

For opaque objects this should probably be multiplied twenty times to enable dark objects to be examined. For high-power dark ground illumination it should be still further increased, and for the use of coloured screens should be again increased. The latter reduce the light from 10 to 200 times.

By means of daylight it is not easy to obtain a greater illumination than, say, 100 candle feet, and therefore, for this reason alone, daylight is not satisfactory for the highest-power work. It is useless for dark ground illumination with even moderate powers or for the use of dark colour screens.

A 10 or 15 candle-power lamp will give sufficient light for all transparent objects when no dark colour screens are employed, and for low-power dark ground illumination, but it is not sufficient for high-power dark ground illumination. For opaque objects the illumination can be so largely increased by the use of a bull's eye that such a lamp is sufficient for most purposes.

If it is desired to use colour screens with dark ground illumination a 100 candle-power lamp is not too brilliant, and enables work to be done which is otherwise impossible.

A case where a very high-power illuminant is desirable is the technique devised by Sir Herbert Jackson for examining objects between crossed Nicols (see page 130).

CHAPTER V

GLARE AND FLOODING

Experiment demonstrating glare—Effect in destroying definition—Conditions under which it occurs—Large light source and wide angle of light—Causes investigated—Reflections from lenticular surfaces—Increased reflection at transparent surface when light is oblique—Surfaces of lenses produce little perceptible glare—Reflection from cover-glass and slip—Multiple reflections between both—Experiments to demonstrate glare caused by reflections between slip and cover-glass—Mounting medium determines amount of reflection—Experiments to show that glare prevents full aperture of object-glass being universally utilised—Different forms of glare—Mounting glare—Lenticular glare—Mechanical glare—Aberration glare—Object glare.

DIRT has been defined as "matter out of place." Glare has been defined as "light out of place."

Experienced microscopists are familiar with the effect observed with certain forms of illumination when, although the microscope in use is of the best, the object appears to be covered with a fog or mist, often to such an extent as to obscure the fine detail and sometimes to render the object almost invisible. The following experiment will demonstrate the effect. Examine a diatom with, say, a 2/3 inch object-glass and a high-power eye-piece, use a wide-angle substage condenser focussed upon the object, and with a flat mirror illuminate the condenser with daylight or light from a piece of illuminated ground glass, not smaller than 2 inches square, placed, say, 3 inches from the mirror. Open the iris diaphragm of the substage condenser to its full aperture, and this appearance of glare or flooding will render a semi-transparent diatom almost invisible.

The same result is observed with a higher power, such as a 1/3 inch or 1/6 inch, the amount of the effect varying according to the details of the illumination.

For the correct delineations of a microscopic object seen with transmitted light, no light should reach the eye that has not passed through the object. The cause of the glare described in the above experiment is that light enters the eye that has not passed through the object. It may have been reflected from the surface of the object or from a substance or surface between the object and the eye, and the contrast between the object and the bright background against which it is seen is reduced.

If a painting is so hung that the glass which covers it reflects the light from a bright window into the observer's eye, he sees but little of the picture, and for the same reason, if light enters

the microscope that has not passed through the object, the microscopist sees but an indistinct picture of the object.

In order to investigate the subject it is necessary to ascertain the conditions under which the glare occurs. Experiments made with objects mounted either dry or in styrax or realgar, show that if such objects are illuminated by a very narrow-angled cone of light, either by the use of a flat mirror alone or by a substage condenser which is stopped down to a small angle by closing the iris diaphragm, little glare can be seen. The most extreme form will be produced when a substage condenser is used with the iris diaphragm opened to give an illuminating cone of great angle or when the source of illumination is large, as, for instance, daylight or an illuminated ground glass.

If the image of the source of light is very small so that only a small patch in the centre of the field of the microscope is illuminated, there will be no glare even with the full aperture of the substage condenser.

If it is not small, but a large portion of the object is illuminated, there will be glare, and it will be quite noticeable until the aperture of the condenser is reduced to about three-quarters of the aperture of the object-glass, being in some cases perceptible until the diaphragm of the condenser is reduced to even one-third of the object-glass aperture.

For example, using an 8 mm. achromatic object-glass 0·5 N.A. with a × 50 eyepiece, which gives a field of view of 0·008 inches, when the focussed image of a Pointolight on the object is 0·00075 inch diameter there is no glare with a full aperture 1 N.A. in condenser ; with the image of the Pointolite 0·00275 inch there is no glare ; with image of the Pointolite 0·00675 inch there is considerable glare ; with ground glass giving very large image, glare is excessive.

In most cases if a ground glass or daylight is not employed the majority of the glare, but not the whole, disappears if the aperture of the condenser is not greater than three-quarters of that of the object-glass ; and it may safely be said that for objects mounted dry or in water, styrax, or realgar three-quarters of the aperture of the object is the largest useful cone of illumination when a large area of the object is illuminated, but that the whole aperture of the object-glass can be advantageously employed if only a small area of the object is illuminated.

Referring to the first experiment with a 2/3 inch object-glass, with a × 25 eyepiece, on such a diatom as Cymbella gastraoides mounted in styrax, even if no substage condenser be used, but the light from an open sky be thrown upon the object by the concave mirror, a large area of the slide will be illuminated and a glare will make the comparatively coarse markings of this diatom very faint. This glare is entirely removed if a black piece of paper with a fine pinhole be placed immediately under the object,

thus reducing the area of the object illuminated without otherwise altering the character of the illumination.

By varying the size of the illuminated area and by varying the size of the cone of the illuminating light it is demonstrated that

1. The larger the area of the object illuminated, the greater the tendency to glare.

2. The larger the cone of illuminating light, the greater the tendency to glare.

The writer when investigating the cause of this phenomenon started with the assumption that it was due to light reflected either directly into the eye from some surface or surfaces between the object and the eye, or to light reflected from such surfaces upon the surface of the object being examined.

The microscope has large numbers of lenticular surfaces, from four to twelve in the object-glass, and four in the eyepiece ; the eye itself has others. The object is mounted on a glass slip with two flat surfaces, and is covered with a cover-glass with two other flat surfaces. It is interesting to note that light reflected back from the upper surface of the eyepiece top lens and from the cornea of the eye can be detected on the surface of an opaque object on the stage of the microscope under suitable conditions.

Most of the reflecting surfaces in a microscope are transparent, and the reflection at transparent surfaces is much greater if the light is oblique. If light falls on a glass plate with a refractive index of 1·5, the approximate amount that is reflected at

0° is 4 %	75° is 25 %
45° is 5 %	85° is 60 %
60° is 9 %	

The amount reflected is small when the incidence is direct, but very rapidly increases as the angle goes up beyond 60°. A series of experiments was devised to ascertain in what manner the majority of the glare was caused. A lens was selected with an aperture of 0·65 N.A. (81°) for the object-glass, and a substage condenser with an angle used as an immersion of 1·3 N.A. ; used dry it was giving a theoretical 1 N.A. ; in practice probably about 0·95 N.A. Thus an object-glass with a moderate angle was used, and a condenser which would give a much greater angle of illumination if desired.

In the chapter on Photometry (page 102), it is pointed out that as much as fifteen times the amount of illumination is sometimes obtained on an object illuminated on a dark ground due to reflections between the cover-glass and the slip ; and this naturally suggests that if an object seen by transparent light has thrown upon it by this means a large quantity of light from above, or obliquely from the side, the black portions would appear grey, or would even be obliterated altogether.

The first experiment was directed to ascertain if the front flat surface of the object-glass reflects much light down upon the object or the cover-glass which again enters the microscope. The diameter of the front surface of the 8 mm. object-glass employed was 0·25 inch, the central portion only of which is used to transmit the light.

The illumination having been arranged to produce glare the effect was observed when an opaque stop with an aperture of 0·07 inch was placed over the front of the object-glass. This allowed all the light that formed the image to enter the instrument. No difference could be observed in the glare whether this stop was used or not, which indicates that whatever glare may be caused by this surface is of little consequence, because reducing the area to 1/15 its area does not produce any perceptible result.

For the next experiment a diatom, Pleurosigma quadratum, mounted on a cover-glass was examined. No supporting glass slip was used. It was observed when the cover-glass was above the diatom and also when the cover-glass was below the diatom. In both cases a ground glass 2 inches square was placed at a distance from the condenser of about 8 inches (focal length of condenser 0·33 inch), and the glare was so great if the aperture was opened evenly slightly beyond that of the object-glass, that all resolution was destroyed. If the ground glass was removed and the Pointolite was almost focussed, full resolution was obtained with the condenser opened to 1 N.A.

It should be explained that the diatom was in very close contact with the surface of the cover-glass, probably having been burnt on.

The cover-glass was then broken and the edges of the broken pieces examined. A diatom was found partly hanging over the edge, hanging in the air so that it had no cover-glass above or below it. Then arranging the illumination to give maximum tendency to glare, the resolution of the portion hanging in mid-air was perfect and free from glare with the full aperture of the condenser, while the portion of the same diatom which was on the cover-glass showed no markings whatever, until by closing the diaphragm of the condenser to somewhat less than the aperture of the object-glass the markings on both parts of the diatom were equally well resolved.

This established the fact that reflection at the cover-glass produced glare, and did so whether the cover-glass was above or below the object if the latter were close enough to the surface. In an experiment when the diatom only lightly rested on the surface, glare was only noticeable when the cover-glass was above the object.

In a further experiment a diatom on a cover-glass was placed with the lower side of the cover-glass in immersion contact with the substage condenser, and although there was a very slight

glare it was scarcely noticeable ; if the immersion fluid, the front lens of the condenser, and the cover-glass had all been of exactly the same refractive index it is possible that no glare would have been visible.

A single flat surface, therefore, is not sufficient to produce glare, and it suggests that multiple reflections of oblique light between two flat surfaces close together, as described on page 103, are the most efficient means of producing the worst results.

To carry the matter to a more definite conclusion a series of experiments were made with the same object-glass. The achromatic substage condenser was strictly corrected for a slip 0·042 inch thick for a distance of 8 inches. To do this a microscopic pinhole was placed 8 inches from the condenser and the correction collar of the substage condenser was adjusted to correct all aberrations. A small circular opaque spot was then placed 8 inches from the condenser and a perfect image of this spot was focussed upon an object which was mounted on the 0·042 inch thick slip. The image of the black disc, which occupied about one-fifth of the field of view, was very perfect, and showed no shade-of greyness round its edges, even if the full aperture of the condenser was used. A ground glass was then placed immediately behind the disc, and the effect of glare was examined as to whether it rendered the black disc grey, or even white.

The objects selected were on slips that were 0·041 inch, 0·0415 inch, 0·042 inch thick, and the condenser was recorrected for each slip to allow for the above small differences. Three of the objects were diatoms mounted respectively in air, styrax, and realgar ; the fourth object was a malaria parasite mounted in balsam ; and the fifth was a plain 3 × 1 glass slip.

The results were as follows :

—	Amount of glare 1·3 N.A. aperture in condenser.	Aperture of condenser at which glare disappears.	Aperture of condenser at which glare lessens considerably.	Increase in glare caused by opening aperture of condenser from 0·65 N.A. to 1 N.A.
1. Plain 3 × 1 slip 0·043 inch thick; in oil immersion contact with condenser.	Practically none	1·3 N.A.	—	None
2. Pleurosigma angulatum mounted under glass in air, slip 0·425 inch. thick, in oil immersion contact with condenser.	Marked	0·15 N.A.	0·16 N.A.	Marked

—	Amount of glare 1·3 N.A. aperture in condenser.	Aperture of condenser at which glare disappears.	Aperture of condenser at which glare lessens considerably.	Increase in glare caused by opening aperture of condenser from 0·65 N.A. to 1 N.A.
2A. Ditto, not in contact with condenser	Very marked, diatoms appeared illuminated on dark spot	—	0·45 N.A.	Marked
3. Diatoms mounted in realgar in oil contact with condenser	Marked, rather more than 2	0·25 N.A.	0·7 N.A.	Marked
3A. Ditto, not in contact with condenser	Excessive. Black spot almost invisible	0·2 N.A.	0·4 N.A.	Excessive. Rapidly improves between 0·6 N.A. and 1 N.A.
4. Diatoms in styrax in oil contact with condenser	Marked. Intermediate between 2 and 3	0·25 N.A.	0·6 N.A.	Marked
4A. Ditto, not in oil contact with condenser	Very bad. Not quite as bad as 3A, but worse than all others	—	0·35 N.A.	Very great
5. Malaria parasite in balsam in oil contact with condenser	Very faint, as 1	0·35 N.A.	None	None
5A. Ditto, not in oil contact with condenser	Faint, more than 5, less than 2	—	0·65 N.A.	Just noticeable

From the foregoing experiments we may conclude that the cause of the majority of glare of the kind which is being discussed originates from light reflected backwards and forwards either along the 3 × 1 slip, the cover-glass, or the medium between the cover-glass and the slip. It may also be increased by reflection between the front of the condenser and the under-surface of the slip. Reflections from the surfaces of the lenses of the microscope do not appear to be sufficient to cause much effect with transmitted light.

We can also gather that little perceptible glare is likely to

occur if the object is mounted in Canada balsam, although it can be observed. If the object is mounted dry, in water, styrax, or any medium that has not the same refraction as glass, there is great tendency to glare.

At a time when the cause and effects of glare had not been investigated, Mr. E. M. Nelson demonstrated that for the resolution of diatoms and Grayson's rulings with a solid axial cone of light, the finest resolution was obtained when the illuminating cone of light was not as large as the full aperture of the object-glass, but was about 7/8 or 3/4 the maximum angle.

His experiments have been confirmed by others, but no satisfactory explanation was given to account for better resolution with the reduced aperture, and the following experiments make a further proof that it is due to the presence of glare.

They were carried out with a 100 candle-power Pointolite lamp about 12 inches from the stage of the microscope, no bull's eye or mirror being used. An adjustable pair of neutral glass wedges was used to maintain an approximately uniform intensity of light in the different experiments. A very perfectly corrected substage condenser with aperture 1·3 N.A. and Wratten gelatine blue and green screens with predominant wave lengths of 4,600 and 5,200 were used. The object-glasses were all, with the exception of the one, purposely out of correction, specially selected for freedom from zonal aberrations.

The Grayson's rulings employed for low powers were bands which increase in fineness in steps of 5,000 between 5,000 and 60,000 lines to the inch; for high powers those which increase in steps of 10,000 from 10,000 to 120,000 lines to the inch.

Experiment 1.

2 mm. achromatic 1·3 N.A.

Blue light.—Iris diaphragm behind object-glass 120,000 lines resolved full aperture—evidently finer lines, if available, could be resolved. It thus formed no test and the iris diaphragm behind object-glass was, therefore, closed till only 80,000 lines could be resolved. (This band was a very regular ruling, and was therefore selected for the purpose.) The iris diaphragm under the condenser was then closed down till only about 7/8 of the full aperture of the object-glass was filled, and it was then found that the aperture of the object-glass could be further closed without destroying resolution, and a point was reached where the 80,000 band was visible with the illuminating cone about 7/8 the aperture of the object-glass, and either increasing or decreasing the aperture of the illuminating cone destroyed resolution. This entirely confirmed Nelson's experiment.

In Experiments 2 and 3 a negative lens combination of a focal

length of about 1 inch was placed in front of the lamp, which reduced the size of the image of the Pointolite to about one-quarter of its previous size, with the following result :

Experiment 2.

2 mm. achromatic 1·3 N.A.

Green Light.—Aperture of object-glass reduced by iris diaphragm at back till 80,000 lines could be just resolved with full illuminating cone. The least reduction of the illuminating cone destroyed resolution.

Experiment 3.

2 mm. achromatic 1.3 N.A.

Green Light.—All conditions exactly the same as Experiment 2, except that negative lens in front of lamp was removed. No trace of the resolution of 80,000 lines could be obtained with any aperture in the illuminating cone.

Experiment 4.

8 mm. achromatic 0·5 N.A.

Green Light.—45,000 lines well resolved.

Blue Light.—50,000 lines well resolved. Full cone of illumination. Cutting down illuminating cone damaged resolution, and resolution disappeared when it was below 0·45 N.A. Cutting down aperture of object-glass so as to only just resolve 45,000 lines, the least cutting down of aperture of illuminating cone below full aperture destroyed resolution. 30,000 lines, the same result.

Experiment 5.

Green Light.—Full aperture of object-glass used. Ground glass placed in front of lamp. Aperture of illuminating cone 1 N.A. 30,000 lines faintly visible. Aperture of illuminating cone 0·5 N.A. 35,000 lines faintly visible. Aperture of illuminating cone 0·45 N.A. 40,000 lines faintly visible.

Experiment 6.

8 mm. apochromatic 0·65 N.A.

Blue Light.—60,000 lines well resolved with full aperture 0·65 N.A. illuminating cone, resolution destroyed directly aperture of illuminating cone is reduced ; only 55,000 visible.

Experiment 7.

16 mm. apochromatic 0·35 N.A.

Green Light.—30,000 lines clearly resolved, but faint, full aperture, 0·35 N.A. illuminating cone. The least reduction of illuminating cone destroyed resolution.

Blue Light.—35,000 lines resolved with full aperture cone, but not if illuminating cone was reduced.

Experiments Nos. 2, 4, 6, and 7 are in direct contradiction to Experiments 1 and 5, and to Mr. Nelson's experiment, and it was considered that the perfection of the corrections of the different portions of the objective for zonal aberrations might have some bearing on the question. Therefore a 2 mm. object-glass was adjusted so that it had a steadily progressive aberration from the centre to the edge; but beyond the fact that it had to be used with different lengths of tube for lines of different fineness, and did not reach so high a point of resolution, it gave no results of interest.

It was evident that the conditions in the different observations were dissimilar in some respect, and the only difference that could be noticed was that the area of light on the object in Experiments 1 and 5 was a larger proportion of the field of the microscope. With a × 25 eyepiece and 2 mm. objective it was larger than the field of view, whereas in all other cases it was a small brilliant patch in the centre of the field, the rest of the field being almost black. Until the introduction of the Pointolite such a condition had not been easy to obtain, and had not been the condition of Nelson's test, where the edge of a lamp flame which more than filled the field in at least one direction was employed.

The results show that Mr. Nelson's experiments and the conclusions he drew were correct for illumination which extended over a large area of the object, and that under such conditions the full aperture of an object-glass can never be fully utilised, unless the object is mounted in Canada balsam or a medium of the same refractive index as glass, or unless some method of eliminating glare such as the polarised light illumination referred to on page 130 is adopted. On the other hand, with a small portion of the object illuminated, the full aperture of an object-glass can be utilised and further resolution obtained.

In carrying out the above experiments both the iris diaphragm and the optical portion of the substage condenser must be accurately centred, because in the observation of ruled lines a spurious resolution can be readily obtained by even a small obliquity of the light.

It has been shown that the majority of the glare usually met with in illumination by transmitted light is caused by reflections either at the surfaces of the glass slip or cover-glass used for mounting the object; it is undoubtedly chiefly caused by the upper surface of the slip acting in conjunction with the under surface of the cover-glass. It may be called Mounting glare, to indicate that it is dependent on the character of the mount by which the object is held. Glare is, however, caused by other means. The surfaces of the lenses undoubtedly cause a slight glare even with transmitted light; with vertical opaque illumination they cause serious trouble, and this form

might be called Lenticular glare. Reflections at edges of the brass mounts of the lenses or the surfaces of the tube or other portions of the microscope may be called Mechanical glare. Another form of glare is dependent on any kind of imperfection in the optical corrections of the lens system. If there is a brilliant point in the object a perfect lens system will bring the whole of the light from this point to an exact point in the image. Any imperfection in the lens system will spread some of this light over other portions of the image and will produce a glare. This glare may be called Aberration glare.

In the case of Mounting glare, when transmitted light is used, or in certain forms of Lenticular glare when vertical illumination is used, the mistiness or fog produced may be so great that an object may be rendered almost invisible. In Mechanical glare or Aberration glare the result will seldom be more than a slight reduction in the contrast, or black and white, of an object. In a delicate structure, where the darkest part is but little different in shade to background, even the slightest haze may destroy the image, and it is for this reason more than for any other that illumination forms so important a feature in microscopic manipulation.

There is another form of glare that depends upon the nature of the object itself which must not be overlooked. It may be called Object glare. It is caused by light reflected from the portions of the object which are not being examined upon those portions which are. In some cases it may be very troublesome ; even such a harmless thing as an air-bubble may direct a blaze of reflected light upon a delicate object in its neighbourhood and flood it with haze, or a strongly reflecting piece of weed or other substance may render objects in its vicinity less distinct.

The methods that are adopted to reduce the evils due to glare are treated in the next chapter.

CHAPTER VI

NOTES ON ILLUMINATION AND TECHNIQUE

High-power transparent illumination—Four conditions to be fulfilled—Methods of filling the aperture with light—Substage condenser—Light scattered by the object—Variation of brilliancy of illumination—Good and bad substage condensers—Effect of unequally illuminated apertures—Best method of using substage condenser—Cutting down aperture of condenser—Focussing illuminant with substage condenser—Area of illumination—Dark ground illumination—Reflection from surrounding objects produces glare—Method of reducing this—High-power dark ground illuminators—Resolution with dark ground illumination—Diffraction effects with dark ground illumination—Stained objects—Importance of mounting medium—Barnard's compressor—Sir Herbert Jackson's method of dark ground illumination by polarised light—High-power opaque illumination—Vertical illuminator—Aplanatic ring illuminator—Polarised light and opaque illumination—The determination of the size of fine structure by diffraction colours—The ultramicroscope—Notes on sand.

High-Power Transparent Illumination

The investigation of ordinary objects, which are well within the resolving power of the microscope, may be conducted without attention to refinements in technique; but even then structural details may be overlooked if the illumination is incorrect. In the examination of structure which approaches the limits of vision, illumination becomes quite as important a factor as the quality of the lenses. From a study of resolution, photometry, and glare, important conditions governing the best methods of high-power transparent illumination can be stated.

1. The whole aperture of the object-glass should be filled with light, to obtain maximum resolution. The whole aperture of the object-glass should also be filled with light to obtain maximum light intensity, but this in itself is not important, as the light can be increased at its source.

2. The light should be equally distributed over the whole aperture.

3. The central portion only of the field of view should be illuminated, in order to prevent glare.

4. The light should not be thrown upon the object at a greater angle than is required to fill the aperture of the object-glass in order to reduce glare.

The aperture of the object-glass may be filled with light in different ways. The object may have such power of scattering light that, no matter how it is illuminated, it will accomplish

this, but if the object is so transparent and free from that form of structure which scatters the light, then it must be illuminated by a cone of light of an angle as large as the angle of the object-glass in use. If a microscope has its mirror removed and is pointed upwards at an unobscured sky, light will pass through the object in every direction, and whatever the aperture of the object-glass it will be completely filled (see Fig. 78). If instead

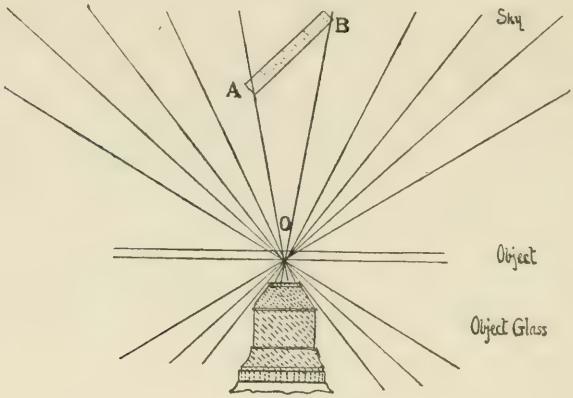


FIG. 78.

of pointing the microscope upwards and taking the light from the sky direct, it is reflected upon the object by a mirror (Fig. 78 A B). The light which reaches the object will be within the cone A O B, which may not be of a sufficient angle to fill the aperture of the object-glass.

To point a microscope upwards at an unobscured sky is inconvenient, but the same result can be obtained by placing immediately below the object a plate of brightly illuminated opal glass, a piece of white paper, or some other material that scatters light in all directions.

It has the result, however, of illuminating a large area of the object, and is for this reason unsatisfactory, as it gives rise to great flooding and glare (see page 106), which ruins the brilliancy of the picture.

Such a method may be used with objects mounted in balsam, in which glare is not so likely to arise, although even then a perceptible amount is present which damages the image.

If a plate of metal with a fine pinhole is introduced between the opal glass and the object it removes the glare by reducing the size of the area illuminated, but it is impossible to place such a plate near enough to the object if the latter is mounted on an ordinary slip to render it effective, except with very low-power

lenses, for if the pinhole is small enough to remove glare it will not allow an angle of light to pass through sufficiently large to fill the aperture of the object-glass. The method is also unsatisfactory on account of the small amount of light which is transmitted by an opal slip of glass.

A substage condenser is the best method of filling the aperture of the object-glass with light. By means of an iris diaphragm,[1] the angle at which the light is thrown upon the object can be completely regulated and the size of the area of object which is illuminated can be reduced by an aperture in front of the illuminant or by using a small source of illumination.

The author is of opinion that the best results will always be obtained if the full aperture of the object-glass is filled with light, provided there is no glare or flooding present; but very transparent objects are exceptionally difficult to see under such conditions. The outlines are sometimes so delicate as to be almost invisible, and are rendered much blacker and more distinct by reducing the condenser aperture, so that the object-glass aperture is not completely filled with light. The image is much more strongly marked, but not so accurately depicted, so that it is often advisable with such objects to work with a small aperture for general observation and to open up the angle of the condenser to study minute structure. Unless some better method of removing glare with transparent objects can be devised, the field illuminated must be less than the total field of view when the full aperture of the object-glass is filled with light.

If the object itself strongly scatters light due to its structure, the aperture of the object-glass is often filled when only a small illuminating cone is used, but the amount of light which is scattered is generally small compared with the direct illumination, and the aperture of the object-glass is not evenly filled. More light passes through the centre than through the marginal portions.

A substage condenser appears to greatly increase the intensity of the light. It only does so because, and in so far as, it fills the aperture of the object-glass. Any other means of filling the aperture of the object-glass, provided it does not absorb light in the process, will produce the same increase in intensity with any given source of light.

It cannot be too strongly urged that when the intensity of the illumination is increased by a condenser, or by other means, the brilliancy of the light should be reduced at its source by means of a suitable light moderator, so that the observer may examine the specimen under a normal illumination. Too great brilliancy will decrease the definition or may render delicate structure invisible.

The use of a bull's eye in combination with a substage condenser does not increase the light (see page 100). It has no useful function

[1] See *The Microscope, a Simple Handbook*, page 26.

in combination with a good substage condenser unless it is desired to increase the area of the object which is illuminated, while it generally interferes with the optical corrections. It is useful with a bad substage condenser and for all forms of opaque and dark ground illumination.

An iris diaphragm is sometimes used over the top lens of the substage condenser to reduce the area of the object illuminated and thus reduce the glare. As previously explained, this is useless unless the object is mounted on a slip as thin as a cover-glass or in a hanging drop. The diaphragm cannot be placed sufficiently close to an object mounted on an ordinary 3 × 1 slip to permit of the full aperture of the object-glass being filled with light.

The disadvantage of the use of a substage condenser is that, unless it is well corrected, it does not distribute the light equally throughout the aperture of the object-glass.

If the eyepiece of the microscope be removed the distribution of the light over the surface of the back lens of the object-glass

Fig. 79.

can be observed. A better method still is to replace the eyepiece and to examine the eyepoint with a powerful magnifier. The apparatus for carrying a magnifier over the eyepiece, described in Chapter VII, page 145, is the most convenient appliance for this purpose. If this examination be made when a well-corrected substage condenser is used to illuminate a wide-angle object-glass, and if a small source of light or a diaphragm with an aperture of about 2 or 3 millimetres close to the light is employed, it will be seen that when the condenser is out of focus a small spot of light is seen in the centre of the aperture of the object-glass. As the condenser is brought into focus this spot steadily enlarges until, when the image of the source of light or its adjacent diaphragm is in focus on the object, the whole aperture of the object-glass is evenly filled with light. This will occur however small the source of light may be. By closing down the iris

diaphragm of the condenser the angle at which the light is thrown upon the object is reduced; and when this angle becomes smaller than the aperture of the object-glass the light will be cut off at the margins of the aperture, and the proportion of the object-glass that is filled with light can be observed when the condenser diaphragm is closed down further.

When a badly corrected condenser, such as the Abbe condenser, is used, the effect is not the same. The light from this class of condenser does not come to one focus: the oblique rays generally come to a focus at a point closer to the top lens than the direct, and the appearances caused at the back aperture of a wide-angle object-glass are shown on the previous page (Fig. 79).

Most of these bad condensers will fill the field of an object-glass which has an aperture less than ·4 N.A. fairly evenly, if carefully focussed, but will not fill the field of an object-glass of a larger aperture, and they only illuminate the outer portion with irregular rings and patches. If the source of light be the edge of a lamp-flame the appearance will be somewhat as shown in Fig. 80.

Fig. 80.

The effect of an irregular illumination of this description may be almost as bad as if the object-glass were covered by an actual diaphragm of the shape of that portion of the object-glass that is not illuminated. The result of such a diaphragm is described on page 74, Fig. 61 *f*.

Fig. 81 is a sketch made of two anthrax bacilli as seen under three different methods of illumination; 1, with the full cone of illumination; 2, with illumination as shown in Fig. 80; and 3, with a stop of the shape of Fig. 80, but placed behind the object-glass. The reproduction of the sketch has made No. 2 appear rather too distinct, but it was somewhat superior to No. 3.

Fig. 81.

There is, however, a means by which the back lens may be evenly filled with light with a bad condenser. If the source of illumination is large, as in the case of daylight, a large flat flame, a ground glass, or a bull's eye, the light is sufficiently scattered to fill the aperture, but in so doing a large area of object, far greater than the field of view, will be illuminated, and there will be a great tendency to glare (see page 106).

If the angle of the light is cut down by the iris diaphragm of the condenser until only three-quarters of the aperture of the object-glass is illuminated, this glare is reduced; but the method of obtaining the best results, when very fine detail is to be observed, is by the use of a small source of light focussed by a well-corrected condenser, so that the image of the light is nearly in focus.

A method of illumination has been suggested in which the back focal plane of the substage condenser is made the luminous source by forming an image of the source of light in this position by means of a bull's eye. Such a process is not convenient, because the image of the source must be approximately as large as the back lens of the substage condenser; but a ground glass placed in this position and brilliantly illuminated by any convenient means has a similar effect, in that the ground glass distributes the light much as though it were a luminous source. This method will fill the aperture of the object-glass evenly with light, but is thoroughly unsatisfactory, because it causes the maximum glare and dazzle that can be obtained with a substage condenser. It illuminates an exceedingly large area of the object, and the glare is so great that it gives a hazy image even with stained specimens mounted in Canada balsam. It also destroys the effective use of the iris diaphragm, which ceases to limit correctly the angle of light which is delivered to the object. The illumination with daylight entering the condenser from all directions is almost as bad, but in practice the mirror at some distance from the condenser prevents the worst effects by partially limiting the angle at which the light can enter. It is best when daylight must be used with a substage condenser to limit the beam of light that falls upon the mirror.[1]

It may safely be said that the aperture of the iris diaphragm should never be opened to a larger size than will admit the angle of light which will just fill the aperture of the object-glass in use, and that when the source of light is large it should not admit more than three-quarters of the aperture of light.

The reduction of the cone of light to three-quarters of the aperture of the object-glass is not a serious matter with low or moderate powers. They generally possess an aperture larger than is required, and for use with eyepieces of moderate power their maximum resolving power is seldom necessary, while if further resolution than that obtained with a low power is desired, a higher power object-glass can be employed. With the highest power object-glasses the limit of resolution is reached, and it is with these lenses that refinements of illumination become of the utmost importance; an eyepiece magnifying $\times$ 25 or even $\times$ 50 is often advantageously used with 1/8 inch and 1/12 inch oil immersion, provided they are properly adjusted and illuminated.

It has been stated that in the opinion of the author the full aperture of the object-glass should be filled with light; some practical evidence in confirmation of this opinion may be of interest.

An experiment of cutting down the aperture of the condenser, and also cutting down the aperture of the object-glass, can be made if an iris diaphragm is attached to the nosepiece of the

[1] See *The Microscope, a Simple Handbook*, p. 43.

microscope behind the object-glass. If the aperture of the condenser is reduced to less than the aperture of the object-glass, the resolution falls off, but not nearly as much as when the aperture of the object-glass is reduced by a similar amount. It appears that the amount of light scattered by even a single small dark object, such as a bacillus, in the centre of a bright field is sufficient to make considerable use of the aperture of the object-glass, when it is not otherwise illuminated by the condenser. To give an example. Two stained leprosy bacilli, very close together in an almost clear field, were examined with a 1/12 inch oil immersion under a full cone of illuminating light. They showed a fine space separating the two, and each bacillus was slightly beaded in shape. By reducing the aperture of the object-glass by means of an iris diaphragm in the nosepiece a point was reached when the two bacilli could not be separated and appeared as one. The illuminating cone of light was then cut down by the iris diaphragm of the condenser, so as to just fill the reduced aperture of the object-glass, and the aperture of the object-glass was opened. The bacilli then appeared as two separate bacilli but not beaded.

In the experiments described on pages 111 and 112, which are illustrations of the effect of glare and flooding, it will be noticed that in resolving bands of ruled lines the reduction of the illuminating cone of light reduced the resolution. This is instructive, in view of the fact that a band of illuminated lines distributes such a large amount of diffracted light that the portion of the aperture of the object-glass which is not filled with direct light is filled with a very considerable amount of diffracted light. An object which consists of a fine regular structure emits a much larger angle of light than that with which it is illuminated.

Examination of the eyepoint will show that with such an object, although the direct light is most powerful, the diffracted light is very intense, and it might have been supposed that the angle of the cone of direct illumination, when such an object is examined, would be of small consequence. The experiments suggest that the intensity of the direct beam is so much greater than the diffracted light that it is the important factor. On the other hand, the experiment described above, of the illumination of the bacillus with a narrow-angle cone, where the light scattered by the object is so feeble that it cannot be observed, indicates that even this small quantity of scattered light has a great effect upon the quality of the image. A consideration of the diffraction patterns produced by bundles of light whose intensity varies in different portions of the bundle would probably explain the observed phenomena.

The importance of focussing the substage condenser so that an image of the source of light is superimposed on the object has been described as the best method of filling the aperture of the object-

glass with light, but when the light source is in exact focus the resolution is not as good as when it is very slightly out of focus. The source of light must be nearly in focus if the aperture of the object-glass is to be filled from a small source of light. The following experiment on Grayson's rulings (see page 153) demonstrates the effect. A 16 mm. apochromatic object-glass 35 N.A., and a substage condenser ·8 mm. focal length, were used, and with the image of the source of light in exact focus 25,000 lines per inch were faintly visible, 20,000 were clearly visible; with the image ·00075 inch below focus 30,000 were clearly visible; with the image ·016 inch below focus 20,000 only could be seen.

It will be observed in such experiments that as the source of light is gradually put out of focus the resolution of a finer band of lines first begins to appear at the indistinct margins of the out-of-focus image of the source of light. This phenomenon has been ascribed to the phase relationship of the light at the level of the object. The author is inclined to consider it akin to the effects caused by glare and flooding, as it does not appear to be noticeable between crossed Nicols with polarised light or when the object is mounted in Canada balsam or some medium of the same refractive index as the object.

The removal of glare and flooding with transmitted light, by reducing the apparent size of the source of light until only a small patch in the centre of the field is illuminated, is an inconvenient method for many observations.

The class of objects which are less seriously affected by glare and flooding are those which are stained and mounted in Canada balsam. Their structure is chiefly determined by the colour. The refractive index of the mounting medium is not of importance in revealing their characteristics. Unstained or uncoloured objects cannot be seen in this manner, and if they have about the same refractive index as Canada balsam they become almost invisible if mounted in this cement. They must be mounted either dry, in water, or some medium which has a different refractive index, and it is in these cases that the utmost care must be employed to avoid glare. When the finest resolution is required the portion of the object that is illuminated must be restricted to as small an area as possible: generally not more than half the field of view. The angle of light thrown upon the object-glass should never be in excess of that required to just fill the object-glass aperture, and for all general work should be about three-quarters of this angle, being cut down still further for searching and for the preliminary observations of very transparent objects.

If a badly corrected substage condenser is used the aperture of the object-glass cannot be filled from a small source of light, and the only thing to do is to use a large source, a ground glass near the source, or a bull's eye, and to stop the condenser to three-

quarters the angle of the object-glass. On stained Canada balsam specimens fair results will be obtained; moderate results may be obtained on other objects, but not the best.

An examination of the figures on page 74 will show that the worst resolution is obtained when the light passing through the aperture of the object-glass is very unequally distributed, such as in Fig. 61 *f*. If the condenser is so badly corrected that it produces distribution of light of this nature, or of rings round the margin, it is better to stop the aperture of the condenser to one-half or even one-third its aperture, and obtain even illumination over the centre, and trust to the scattering produced by the object to make partial use of the otherwise unilluminated margin of the aperture.

Dark Ground Illumination.

Objects which are entirely opaque, unless they are of small size, must be illuminated by light being thrown upon them from above; that is, from the observer's side. They reflect back the light or scatter it in all directions, and behave as if they were self-luminous objects. Some notes follow later upon this so-called "opaque" illumination, but these remarks apply to what is known as dark ground illumination.

Almost all objects, even if perfectly transparent, have the power of reflecting light. A plate of the clearest glass reflects a proportion of the light which falls upon it; in fact, if the incident light is oblique the proportion which is reflected is large (see page 107). Thus almost all transparent or semi-transparent objects can be seen by reflected or scattered light under suitable conditions. When the light is thrown upon them from below, from the side away from the observer, and it is done in such a manner that it does not directly enter the microscope but illuminates the object on a dark ground, such a method is called dark ground illumination.

The general conditions necessary for dark ground illumination are given in the Simple Handbook on the Microscope, but some further notes on this subject are here added.

One of the difficulties that will be experienced with dark ground illumination is the examination of thick specimens.

If an object examined by dark ground lies in a mass of material that reflects light, the advantage of this form of illumination may be lost. A delicate piece of lace which is brilliantly depicted when it is placed upon black velvet is almost invisible on a piece of white paper. Although it is generally possible to isolate the object to some extent it is often difficult to remove all the extraneous matter, and the glare produced by reflection from surrounding particles may be very troublesome.

This glare can be modified to a certain extent. Fig. 82

shows how the light thrown by a high-power dark ground illuminator impinges upon the object in a fine hollow cone meeting at a point. The point is a minute image of the source of light; it has a certain size: but if the illuminator is very perfectly corrected and the source of light is small, as with a Pointolite or an arc lamp, and is not nearer than 10 inches from the microscope, the size of this image will not exceed 1/1,000th of an inch.

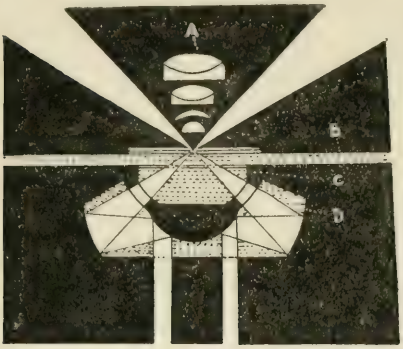


Fig. 82.

With the focussing model of the dark ground illuminator this image can be moved up and down through the thickness of the specimen under examination, and a great deal of the glare can often be got rid of by so focussing it that the extraneous matter is not illuminated. In this case no bull's eye condenser must be employed between the light and the illuminator. It was shown in the chapter on photometry that the bull's eye produced a large increase in light under dark ground illumination, because it produced a large image of the source of light which by reflection between the cover-glass and the slip increased the intensity; but in this particular case, where it is required to specially restrict the illumination to as nearly one point as possible, the bull's eye must not be made use of.

In general, the specimen to be examined by dark ground illumination should be as thin a layer of illuminated material as possible.

Very striking and interesting results may be obtained by dark ground illumination with low-power lenses. For instance, the green variety of the animalcule known as "Stentor" will appear blood red on a black ground. No special difficulties are met with, with low powers, either with the use of the substage condenser and a patch stop, the spot lens, or the Wenham paraboloid; such pieces of apparatus illuminate a large area of the object and need not have any pretensions to optical excellence. Nothing is required but to converge the light upon the specimen at an angle that is greater than the comparatively small aperture of the low-power object-glass.

High-power dark ground illumination requires more accurate illumination and more careful adjustments. Great care must be taken with the centring of the illuminator. If a semi-transparent object is illuminated by more light upon one side than on

the other, one margin of its outline may appear more distinctly than the opposite one, and a false appearance will be produced. A method of centring is given in the Simple Handbook on the Microscope, but with a research microscope such as the "Massive" or "Radial Research," where the illuminator can be rapidly changed for an achromatic condenser without tending to move the adjustments of the instrument, a more accurate method may be employed. The achromatic condenser being in the substage, its iris diaphragm may be centred with the object-glass which is to be employed, using a low-power eyepiece (*The Microscope, a Simple Handbook*, page 29). The source of light having been focussed, its image should be placed in the exact centre of the field of view by moving the flat mirror of the microscope. The dark ground illuminator is then put into the substage of the microscope in place of the achromatic condenser, and focussed, the diaphragm being fully opened. The centring screws of the substage are then moved until the image of the source of light again occupies the centre of the field. This must be done without a bull's eye condenser between the source of light and the mirror, although for reasons which are explained on page 101 a bull's eye will often be used after the centring is accomplished in order to increase the light. The difficulties in resolution met with in transparent illumination and discussed in the last section do not appear with this form of illumination. To those who are familiar with the difficulty of obtaining the ultimate resolution with transmitted light, it is a matter of surprise that the best resolution and definition will appear immediately, provided the light is central and that the dark background is not interfered with by light reflected from some lower layer of material or floating air bubbles. The mystery of how to obtain the best resolution has disappeared. There is no glare or flooding and the whole aperture of the object-glass is evenly filled with light so as to give maximum resolution.

There is no foundation for the statement that has been made that this form of illumination does not give the full resolving power of the object-glass in use. Anything that can be resolved by transmitted illumination can be resolved by dark ground illumination, and in general with much greater brilliancy, because of the increased contrast between different parts of the structure.

A good example of this is the resolution of Pleurosigma angulatum into dots with an 8 mm. achromatic object-glass with a N.A. of only 0·5. Unless the zones of this lens were almost perfectly corrected it could not be resolved with so small an aperture. Carpenter mentions 0·65 N.A. as the smallest aperture with which P. angulatum had then been resolved.

With transparent illumination and a condenser with a cone of the full 0·5 N.A. and a × 50 eyepiece, it cannot be resolved with

red or orange light, rather faintly with green, but brilliantly with blue light.

Such an object can be resolved by this lens with light of short wave length, but not with light of long wave length. It is therefore on the theoretical limit of this aperture, and forms a good test of resolution by dark ground illumination. It is perfectly resolved into dots with green or blue light under dark ground illumination, and is far more brilliant than with transmitted light. With transmitted illumination it is difficult to get resolution unless the diatom is mounted in realgar or dry. With dark ground illumination the resolution is also perfect with specimens in styrax or monobromide of naphthalene. It cannot be resolved with red or orange light. It would therefore appear that dark ground gives equal but no greater resolution, but much greater contrast, so that diatoms unresolved because of lack of contrast by transmitted light are readily resolved by dark ground illumination.

A further example of resolution with dark ground illumination with a high-power object-glass gives the following results:

A 1/8 inch (3 mm.) oil immersion Beck achromatic object-glass 0·95 N.A. on Amphipleura pellucida, light "Pointolite," perfectly corrected achromatic 1·3 N.A. condenser, solid cone about 1 N.A., gives no resolution with transmitted light of any colour on specimens mounted in styrax or monobromide of naphthalene. With specimens in realgar and dark blue light, line resolution just glimpsed, but not actually seen, but signs of structure are visible. With dark ground illumination and specimens in either realgar, styrax, or monobromide, resolution into lines is thoroughly distinct with blue or green light. In realgar it is thoroughly black with blue light, good with green, faint with white light, not visible with red light.

There are cases when the refractive index of the object is so nearly the same as that of the medium in which it is immersed that its reflecting power is small, and an extremely powerful illuminant is required to enable it to be seen; but in such cases it is usually almost impossible to distinguish by transmitted illumination, and even here an advantage may be gained by dark ground illumination.

There is an important characteristic that applies to dark ground illumination. On pages 73–76 there are diagrams of an image of a point of light as seen through an optical instrument. With a circular aperture it is shown in Fig. 60 *a* to be a small circular patch surrounded by rings, and it is assumed that in ordinary vision such rings are too faint to be visible. This is not the case with dark ground illumination when the specimen has great power of reflection and the light is very intense. The image of such objects as bacteria or micrococci, when the light is intense, show a fine line around them of the same shape as the

specimen, which might be taken for an envelope or for the true margin of the object. This is generally caused by the first and most brilliant diffraction ring in the image of each point of the object, and if an iris diaphragm be placed behind the object-glass the fine surrounding line of light will be observed to move further away from the main body of the bacillus when the aperture of the object-glass is reduced. If it were actual structure there is no reason why its position should alter by reducing the aperture of the object-glass, it would only become less well defined. The secondary images of this nature are not so apparent if the light is not so intense, and a means of graduating the intensity of the light is most desirable for careful work.

The use of colour screens on stained specimens under dark ground illumination is worthy of careful attention. The bacillus anthrax, stained so that by transmitted light it appears blue, when viewed by opaque illumination and a purple screen which transmits only blue and red light reflects red and appears of a blood-red colour. Under similar conditions tubercle stained red appears by reflected light a light green. The tubercle stands out much more vividly than is the case with transmitted illumination. Indeed, the way in which stained bacteria mounted in balsam stand out from their surroundings, quite apart from their colour, suggests that they have a very different refractive index to balsam. A specimen of the signet-ring form of malaria in a similar manner is very distinctly differentiated from the blood corpuscle in which it is encysted.

The resolving power of an object-glass under every kind of illumination is directly dependent upon its aperture (see page 66); and if further resolution is required than that which is given by an aperture of 1 N.A., the object must be immersed in a medium of higher refractive index than 1, or no light of a greater angle than 180° in air (1 N.A.) can reach the object-glass. There is some reason to believe, however, that objects mounted in air which are in extremely close contact with the cover-glass may emit some light beyond 180°, for if siliceous structures, such as diatoms, are burnt on to the under surface of a cover-glass (a very common practice in mounting diatoms "dry") experience points to the fact that the surface of contact is immersed in the glass and a correspondingly increased resolution is observed, and it may be that objects in water which are in close contact with the glass may show similar characteristics, but in general it may be concluded that objects mounted dry will not show finer structure than that resolved by 1 N.A., objects in water 1·33 N.A., and so forth, dependent on the refractive index of the material in which they are mounted; and that those mounted in Canada balsam or any material equal to or higher than the refractive index of glass will show structure corresponding to the maximum resolving power attainable with any object-glass.

With dark ground illumination the object-glass employed can never be used with the maximum aperture attainable, because some portion of the maximum aperture must be utilised for the purpose of illuminating the object with light that will not enter the object-glass. Fig. 83 shows an object in a layer of water, illuminated under dark ground illumination. The light from A to B and C to D between 1·2 N.A. and 1·33 N.A. is illuminating the object, and the object-glass must not receive any of this light directly, but only the portion that is reflected by the object, otherwise there would be no dark background; therefore, the object-glass used to observe objects in water under dark ground illumination cannot have an aperture greater than about 1·2 N.A., and the theoretical resolution is slightly reduced compared with the resolution by transmitted light where an angle of 1·33 N.A. can be employed. A special focussing dark ground illuminator has been invented by R. and J. Beck, Ltd., which allows the use of an object-glass of 1·2 N.A., provided the objects are mounted on slips not thicker than ½ mm., and considerable advantage has been realised by this increase of available aperture. The same illuminator is suitable for an object-glass with an aperture not exceeding 1 N.A. when used on a slip between 1 and 1½ mm. thick.

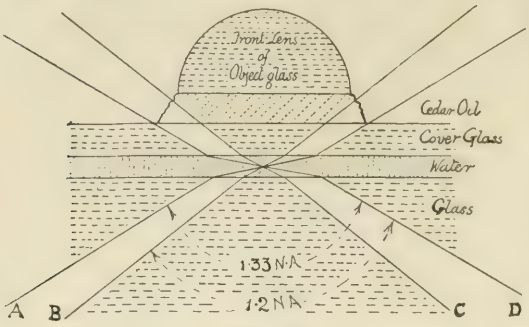


FIG. 83.

NOTE.—At the request of Mr. J. E. Barnard, of the National Institute of Medical Research, Messrs. Beck have produced a special illuminator which permits of the use of an object-glass with an aperture of 1·27 N.A. This has been used with success on objects in water. It requires somewhat more accurately centring than is required on the other illuminators, but this is readily accomplished on the "Massive" or the "Radial Research" microscopes. An experimental illuminator has been made which can be used with object-glasses of 1·4 N.A. if the object is mounted in a medium of sufficiently high refractive index.

With all high-power dark ground illumination great precision is necessary in the construction of both object-glasses and illuminators. From the examination of Fig. 83 it is evident that the illuminator must be free from all errors in aberration or the

light would not be confined to sharply defined angles. The only form of illuminator that has yet been made that is sufficiently perfect in this respect is the double reflecting concentric type (Fig. 82), and it is necessary that the object-glass should be originally made with the correct limiting aperture. If a large aperture lens is stopped down by means of a stop behind the lenses it admits direct light unless it is stopped down to a considerably lower aperture than is necessary when the object-glass has its aperture limited in the correct place, namely between the lenses of the combination.

It so happened that at the time of the introduction of the dark ground illuminator, which enabled a 1·2 N.A. object-glass to be used, the National Institute of Medical Research was investigating a new micro-organism. With an object-glass of ·95 N.A. it appeared to be a row of connected dots like a streptococcus. When it was examined with the new illuminator and a 1·2 N.A. apochromatic object-glass its true shape was readily seen to be a complete spiral and that the appearance of dots was due to an indistinct image of the convolutions.

Dark ground illumination renders the outlines and structure of delicate structure visible that cannot be seen by transmitted light. No attempt to diagnose such organisms as diphtheria bacilli should ever be attempted with any other form of illumination, whether they are stained or living specimens, as the chance of wrong diagnosis is greatly reduced when the organisms are examined with dark ground illumination.

With the 1·2 N.A. dark ground illuminator the feather of light which is thrown upon the object is so narrow, and the illuminated point in the centre is so small, that only an exceedingly thin layer of the object is illuminated, and if no bull's eye is used and the light is taken direct from an arc lamp much of the work on colloid solutions can be done that has hitherto required the far more elaborate Siedentopf apparatus described on page 185. The solution to be examined can be placed between a slip and cover-glass carefully selected for the excellence of their polish and can be examined by either a dry or immersion lens.

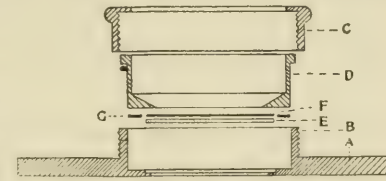


FIG. 84.

A practical difficulty met with in the examination of living organisms with oil immersion lenses under dark ground illumination has been overcome by Mr. J. E. Barnard, who has designed a new form of compressor (Fig. 84) which clamps the cover-glass on to the glass slip. This prevents the cover-glass being lifted by the suction of the oil as the immersion object-glass is focussed

and prevents the cover-glass and thin slip from being bent so as to deform the water holding the organisms into a lens which injures the definition. It consists of a thick metal plate, A, 3 inches × 1½ inches, which can be used on any ordinary mechanical stage. Projecting from this plate and forming an integral part of it is a tube, B ; inside this tube a pressure plate, D, loosely drops, which can be held firmly down by a screwed collar, C. The pressure plate, D, has a pin which fits a slot in the ring, B, which prevents it from rotating as the collar, C, is turned. The plate, A, has a circular recess into which a circular glass plate, E, is dropped. This plate may be either ½ mm. or 1 mm. thick, according to the aperture of the object-glass used (see page 128), and a cover-glass, F, of the same size is placed over the lower plate.

The fluid to be examined is placed between the glass plates, E and F, and the pressure plate, D, is held down upon them by the screwed collar, C, so that they are firmly held but not crushed. A washer of paper or card, G, may be inserted if desired of such a thickness to ensure that the layer of liquid is of a definite depth. The centre portion only of the discs over an area of about ¼ inch can be examined when a high-power illuminator is in contact with the lower surface of the glass plate, E, but this is generally sufficient for bacteria and small organisms and for small ultra microscopic particles. If desired the plate can be provided with three levelling screws for adjusting the horizontal position, but these are not generally required.

There is another method of illumination which was first employed by Sir Herbert Jackson in work on the examination and identification of small particles in various media, notably in glasses and glazes, and he also employed it for the study of a number of other objects, including diatoms. It gives somewhat the same appearance as dark ground illumination, in that the object stands out more brightly illuminated than the background, and has the same merit of showing no glare, giving good contrast, and filling the whole aperture of the object-glass with evenly distributed light, and there is no restriction to the aperture that can be used. It consists of the use of a polarising apparatus in combination with a wide-angle substage condenser. A polarising prism below the condenser illuminates the object with plane polarised light (see page 196); that is to say, the object is illuminated by light that is all vibrating in one plane at right angles to the optic axis of the instrument, and if an analyser be placed over the eyepiece of the microscope in a "crossed" position, at right angles to the polarising prism, no light that is vibrating in this plane can pass through. But it is a property of reflection from most fine structure that some of the reflected plane polarised light is eliptically polarised, and if the object has the power of reflecting the light in all directions some of this reflected light will no longer be in the plane of polarisation and will pass through

the analyser over the eyepiece, with the result that the small reflecting elements show up brightly on a relatively dark ground. Each reflecting point in the object is illuminating the portions around it with this elliptically polarised light, and a completely illuminated object is seen.

The light so reflected is somewhat faint, and a powerful source of illumination is essential. This method has the disadvantage that the field is not entirely black, because no polarising apparatus is so perfect that it entirely stops all light. Nevertheless the contrast between the illuminated object and the background is very considerable.

An interesting experiment to show the elliptical polarisation by reflection can be made by examining a small mercury globule between crossed Nicols when it is illuminated by a wide angle condenser; the ring of light reflected by the edge of the globule is elliptically polarised and appears bright on a black ground except for four small portions at 90° to each other.

It is essential for the use of this polarised-light method that the object should be under the most favourable conditions for reflecting light, and it might appear that such an object as a diatom must be mounted dry in order to possess a great difference in the refractive index between the object and the mounting medium, and thus to have a sufficient power of reflection. The reflecting power is, however, so much increased by the angle at which the light impinges upon it (see page 107) that by the use of a wide-angle condenser, preferably an immersion condenser of about 1·3 N.A., beautiful resolution of diatoms mounted in styrax, monobromide of naphthalene, or realgar is obtained. It is far superior to the resolution obtained with ordinary transmitted light, and such a diatom as Amphipleura pellucida can be seen as if it consisted of dots with a 1/12 inch achromatic object-glass, 1·25 N.A.; and with an apochromatic of 1·4 N.A., the dot resolution is quite convincing. The combination of a patch stop with the polariser and the condenser is useful, as it has a tendency to reduce the light other than that reflected from the small elements of the object. The combination of the dark ground illuminator and the polarising apparatus also gives most striking results.

Certain forms of animalculæ and bacilli can be seen by this form of illumination in a manner that may be of great interest, but the method has only a limited application to such transparent objects, due to the small amount of light they reflect.

With all forms of high-power microscopic observation great care in the interpretation of the results must be taken. It requires to be considered in connection with the method of illumination and in connection with the large angle of light which is received from each point of the object. If we could see a small object placed, say, one eighth of an inch from the eye, we should be able to see not only its upper surface but all round its sides,

and that is what a wide-angle object-glass is doing. It is a form of examination with which we are unfamiliar, and it is not surprising that certain microscopical images are difficult to understand.

The use of the fine adjustment rapidly focussed up and down through an object of appreciable thickness forms a help in the process of visualising an impression, and the use of a high-power binocular microscope is of still greater value.

High-Power Opaque Illumination

The use of a bull's eye for low-power opaque illumination is described in *The Microscope, a Simple Handbook.* The following notes refer to a high-power opaque illumination.

Until recently the usual method of obtaining opaque illumination with high powers was by means of the vertical illuminator (see *The Microscope, a Simple Handbook,* p. 40). The light is thrown through the object-glass in use upon the object. Thus the object-glass acts as a substage condenser, converging the light upon the object in a cone of the same angle as the aperture of the object-glass itself. The Beck Aplanatic Ring Illuminator, which throws light upon the object from outside the object-glass, illuminates the object by means of a hollow cone which is of a larger angle than the aperture of the object-glass. This ring illuminator can be used on object-glasses of as high a power as 4 mm. (·85 N.A.), and forms a second method of opaque illumination with high powers.

If the object being examined has an irregular surface that scatters light in all directions the method of illumination is of little consequence, except in so far as it produces shadows. Such shadows are often of use in helping to interpret the structure if the direction of the light is changed while they are examined.

Objects examined by means of light thrown upon them through the object-glass from above, by a vertical illuminator, do not give the appearance of opaque illumination if they are small and are mounted upon glass. The glass acts as a mirror and reflects the light back through the object, so that a dark background is not obtained.

The object is viewed by transmitted light, which is produced in a special manner; but it is not opaque illumination as generally understood. The object is seen partially by the light reflected from its upper surface and partially as an opaque object against light thrown through it from behind. The image suffers from mounting glare explained on page 105. Examination of objects by this method require the light to be focussed as though they were illuminated by a substage condenser, otherwise it will not fill the whole aperture of the object-glass. To do this, the light must be at the same distance as the eyepiece is from the vertical

illuminator, but it is doubtful if this method of illumination has much to recommend it, except that it enables the full aperture of a wide-angle immersion lens to be employed without some of the mounting glare connected with transparent illumination. It is accompanied by a lenticular glare, which is frequently more troublesome.

To give a true opaque illumination small objects to be examined should be mounted without cover-glass upon some non-reflecting matt surface, such as black paper.

The examination of metal surfaces by high powers requires this so-called opaque illumination. The surfaces are generally polished and etched; the effect obtained is a brilliant image formed by the light being reflected back along the direction of incidence, and any portions that do not reflect show up more darkly, like an ink spot on a silvered mirror. The structure of the specimen is determined by the differences in reflecting power as regards brilliancy and colour of the separate elements. The polished portions give a direct reflection, the unpolished parts scatter the light. As regards the light directly reflected it may not on its return journey fully fill the aperture of the object-glass unless the source of light is in focus upon the specimen, but as regards the scattered light from these portions of the object which do not give a direct reflection this always fills the aperture. The manner in which the light reaches them does not affect this property, because it is scattered by them in all directions. It is not of the first importance for this class of work to insist on any particular position of the light source, but it is probably best to have the light source at about the same distance from the reflector as the eyepiece.

The difficulty with this illumination is the lenticular glare produced by light reflected from the surfaces of the lenses of the object-glasses through which it is thrown. It cannot be entirely eliminated ; the most important point is that what is thus reflected should not be concentrated upon any particular patch in the image, but should be evenly distributed.

The Aplanatic Ring Illuminator throws light upon the object from outside (see page 97, Fig. 73), and has the curious result that as it only allows scattered light to enter the object-glass it renders a polished surface dark instead of bright, and reverses the light and shade. It has great value in determining structure, as it gives to a surface the appearance that it has when examined by ordinary diffused light by the naked eye.

Its use for the examination of fine opaque articles or coloured materials, especially in combination with polarised light, is invaluable. True colours of chemical substances can be recognised when the light directly reflected is quenched by crossed Nicols ; the material is visible by the light reflected by the particles amongst themselves, and which, being elliptically polar-

ised, can pass through the analysing Nicol prism. This method was developed by Sir Herbert Jackson in his work on Ceramics and Glass, and forms a part of the technique previously referred to, which was devised by him for this purpose.

Notes on the Examination of Fine Particles

Some objects, when examined by a microscope, under certain conditions appear to be brilliantly coloured, but show no colour when the conditions are varied.

An experiment with a glass plate with a series of parallel lines ruled very closely together on the surface will explain the cause of the colour caused by diffraction from a fine regular structure.

Suppose that such a ruling, say 15,000 lines to the inch, be placed on the stage of the microscope, and that an object-glass be used to examine it which has an angular aperture of 12°, and that a small parallel beam of white light is thrown along the optic axis of the microscope from below through the grating, Fig. 85, 1.

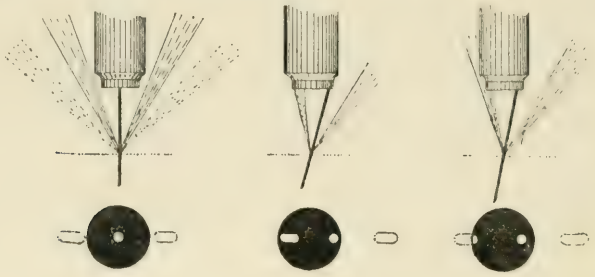


Fig. 85.

When the beam of parallel light meets the grating a portion of the light passes through direct, but some of the light is diffracted and is emitted at definite angles dependent on the fineness of the ruling. One beam of light in addition to the central beam will be emitted on each side at an angle of about 14° for blue light, a second at another angle somewhat greater, and so on. The angle at which the first beam of light is emitted depends on the formula $\lambda = E \sin \theta$ where λ is the wave length of the light, θ the angle with the central beam, and E the distance apart of the lines.

As white light consists of light of all colours, each of which has a different wave length, the above formula indicates that the angle of the different colours will be different, and the beam of diffracted light will be a fan-shaped beam blue inside, then green, orange, yellow, red, in the order of the spectrum. It is, in fact, a pure spectrum formed by a diffraction grating.

In the diagram, Fig. 85, 1, these coloured diffraction beams have no effect on the image, because they do not enter the microscope, and the only light by which the ruled lines or grating is seen, is the central colourless beam. Fig. 85, 2, shows a similar illumination by a parallel beam of light, but thrown through the grating obliquely, and the two diffracted beams which still retain a constant angle with the central beam are then in such a position that one does not enter the microscope, but the whole of the other is included in the angle which enters the object-glass. Again, the effect will be a colourless image of the grating, for although the coloured diffracted beam is included, this beam, which contains all the constituents of white light, is reunited when it reaches the image plane of the microscope and gives rise again to colourless light. But suppose the obliquity of the light (Fig. 85, 3) had not been quite so great as shown in Fig. 85, 2, then the direct colourless beam would enter the microscope, together with a portion only of the diffracted beam; for instance, the blue light only and the image in the microscope would be formed by a mixture of white and blue light and the object would appear to be of a bluish tinge.

Another case is illustrated in Fig. 86, in which the light is more oblique, and the aperture of the object-glass is such that the only light that enters the microscope is the blue of the first diffracted beam. In such a case as this the only light that enters the microscope is blue, and the grating appears a brilliant blue. If the obliquity of the light is increased the image will be formed by a combination of blue and green light, and as the obliquity is further increased the colour of the grating will change until, when all colours of the spectrum are included in the beam of light which enters the microscope, the grating will again appear to be colourless.

Fig. 86.

In this way objects which are composed of nothing but black and white lines may appear brilliantly coloured, and the colour will vary according to the obliquity of the illumination and the angular aperture of the object-glass. If the eyepoint be examined with a magnifying glass, or if the eyepiece of the microscope be removed and the back of the object-glass examined, the appearance will be as shown below each diagram in Figs. 85 and 86. Suppose that in the case shown in Fig. 86 the illumination had been not a single beam but a ring of oblique light formed by a substage condenser with a patch stop behind it, then the effect would have been the same, except that more light would have been thrown into the object-glass. It would still be all blue, and if the lines were turned round on the stage of the microscope, or if there were lines in all directions, provided the lines were all

of the same fineness, the colour would be the same, and the colour of the light is an indication of the fineness of the lines. With a knowledge of the obliquity of the illumination and the aperture of the object-glass the degree of fineness of the lines can be estimated.

A diatom or insect scale has a regular structure which has the regularity of a series of ruled lines, and the colour phenomena here described are produced by such objects which are colourless under suitable illumination.

The condition referred to in the chapter on Resolution, which must be satisfied in order that fine lines shall appear resolved as separate lines, requires that the angle of the object-glass shall be of a certain size compared with the fineness of the lines. It so happens that this angle is exactly the same as the condition shown in Fig. 85, 2, where the direct beam of light and one spectrum of colours can be included in the aperture; and one condition where an object shows colour is when the aperture of the object-glass is just insufficient to resolve the lines or structure of the object.

Fine particles are not as a rule arranged at exactly equal distances apart, but where such is the case the same colour effects are visible.

By careful study of the colours produced with different apertures of both the object-glass and the illumination, the distance apart of the lines or particles of a regular structure may be estimated with considerable accuracy, even where they cannot be seen as anything but a coloured structureless mass.

This method of measurement can be applied to structure that is not below a certain limit of size. The limit can be calculated from the equation $\lambda = E \sin \theta$, for the sine of 90° is 1, and no angle can be obtained greater than 90° from the vertex. If the direct light, as in Fig. 85, 2 is almost at grazing incidence, then a diffracted beam could be received by an object-glass almost at 180° to the direct beam; and the limit up to which this system of measurement can be used is where the distance of the structure is greater then $\frac{\lambda}{2}$, or say 1/100,000th of an inch, or 1/4 μ. Many of the colour effects produced by regular structure are due to this cause. The colour in thin films or in such minerals as opal, in mother of pearl, and numbers of other substances, are caused by an interference of light, and do not represent any intrinsic colour in the object itself. The effect is only caused in regular or periodic structure; it does not occur if the structure is irregular; and the question as to whether, when irregular particles are below a certain size, they appear to be of a particular colour on account of their size alone opens up a further interesting subject.

Mr. Chapman Jones made a series of interesting experiments in 1911, and in a paper published in the *Photographic Journal* of

that date he describes the colour of particles of which he had estimated the size by an indirect chemical process. His work goes to show that their colour is dependent on their size and not upon their distance apart. Subsequent investigations appear to show that although particles of silver which were there discussed by Mr. Chapman Jones followed a certain law as regards their size, different materials did not give similar colours, and that colour has relation to the characteristic crystalline shape of the material itself as well as to the size of the particles.

The examination of particles that are too small to be readily seen even with the highest-power microscope has become a subject of great importance in several branches of work. They include the study of colloid solutions which contain particles, some of which are quite invisible under the ordinary microscope. In connection with certain diseases fine particles have been discovered which appear to be characteristic and which are just below the limit of microscopic vision and can only be rendered visible when they have been stained. The process of staining adds a layer of material to their surface and by this means increases their size to an extent that renders them visible under the highest powers.

The presence of certain fine particles that are invisible by the ordinary microscope can be ascertained. A star which is so far away that it has no apparent size can be observed because it sends out a sufficiently powerful beam of light to affect the retina of the eye. It appears as a point of light. If a particle of matter can reflect a reasonable proportion of the light that is thrown upon it, and if a strong enough light can be used, it also can be observed, although it may be far smaller than any microscope would show under ordinary circumstances. An apparatus has been invented which accomplishes this, and which has been termed the ultra-microscope. When particles can thus be made visible a great deal can be learnt about them. Their numbers can sometimes be estimated, the movements can generally be observed, and the regularity of their distribution. Changes in their numbers, their movements, or their distribution during treatment by chemical, electrical, or physical processes may point to their properties or habits.

For instance, if any of these particles are alive it may be possible to obtain information as to processes that will kill them. Chemical reactions may be observed, and the use of the ultra-microscope, which at first sight appears to be of somewhat academic interest, is a scientific tool of considerable value.

The ultra-microscope is not a microscope, but a set of apparatus that can be used with any good ordinary microscope. The apparatus [1] consists of a powerful light (A) (Fig. 87), a lens (B) to condense the light upon an adjustable horizontal slit (C),

[1] See also p. 185.

a lens (D) which forms an image of the slit (C) at the position (E), about 1/5th the size of the slit, and an object-glass (F) which forms a second image of this slit ten times smaller than the first image.

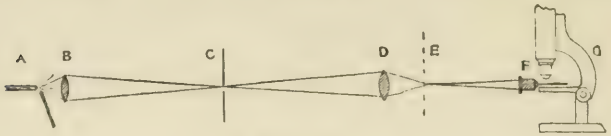


Fig. 87.

The result is that the combined apparatus sends out a fine feather of light which at the focus is only 1/50th the size of the slit (C) in width. If the slit (C) be set to a width of 1/10th of a millimetre the feather of light is only 1/500th of a millimetre, or about 1/12,000 of an inch in thickness. This beam of light is thrown horizontally through the fluid containing the particles to be examined, and the microscope is placed at the position (G), with its axis in a vertical position. It is necessary to illuminate a fine layer of the fluid only, because, if a thick layer is illuminated, so much light comes from the out-of-focus images of the particles, above and below those being observed, that the field is filled with a mist of light which obscures the images of the particles. It is necessary to use an arc lamp, as the light must have a great intrinsic brilliancy. If the particles are almost of a microscopic size a Pointolite can sometimes be employed, but the latter has only about 1/10th the intrinsic brilliancy of an arc lamp.

The Radial Research microscope (see page 170) is particularly suitable for this work, because the stage of the microscope can be focussed up and down in order to place the fluid to be examined in the correct position; and the square-stage model, having the central portion of the stage cut away, allows the object-glass of the ultra-microscope apparatus to be brought close to the apparatus which holds the fluid.

The apparatus employed for examining fluids for chemical purposes has generally been made from a tube blown into a bulb in the centre. This bulb is ground away on two sides and two thin glass windows are attached. Through one of these the feather of light is thrown, and through the other the observation is made.

Fig. 88.

Where the particles to be examined are of a comparatively large size and can be rendered less numerous by dilution, the Beck dark ground illuminator can be used for ultra-microscopic work. The size of the central patch of light, if taken from the crater of a small arc lamp without a bull's eye, is less than 1/1,000 of a inch in depth. It is formed by a ring of light which can be turned into two

almost horizontal beams in one meridian by placing a slit below the illuminator, and this forms a very satisfactory ultra-microscope for purely observing purposes if the particles are not too small.

An advantage that the more elaborate apparatus possesses, however, is that a measurement can be made with a micrometer of the width of the slit by revolving the slit into a vertical direction for the purpose. The slit having been replaced in a horizontal position, a square can be placed in the eyepiece which represents a definite area on the object space, and a count of the number of particles in this area will give an approximate idea of the quantity contained in a definite cubic capacity.

The examination of fine particles is not confined to those held in suspension in fluids; many solid bodies, such as coloured glass and certain forms of crystals, contain particles of ultra-microscopic size, and their study is of considerable importance to the chemist and petrologist.

The study of particles in such materials as clay and mud leads to the consideration of the somewhat larger particles of silt and sand.

Particles of rock between the sizes of 1/10 millimetre and 2 millimetres are classified as sand. They have many uses in industry. They form a raw material for glass, bricks, cement, concrete, and a number of other products, and their suitability for the purpose for which they are required is largely determined by the microscope. Their size and shape can only be determined by this means; and as most sand consists of powdered rock of crystalline formation the petrological microscope is the best means of ascertaining their composition. When sand is to be used for moulds for making metal castings its composition and the size and shape of its particles are all-important, and also the material of a fine nature with which it is mixed, which will form a means of assisting the particles to adhere together during the process for which it is to be used.

The sharpness of the grains varies greatly in different kinds of sand, and examination under a microscope will determine the best kind for use as a grinding material for different purposes.

The measurement of the particles is readily accomplished by one of the methods explained on pages 157–158, and observation will generally give sufficient indication as to regularity in size. For accurate work, counting processes of particles larger than a specified size may be employed, though it is better to use the elutriating process, which consists in collecting the particles which settle down in a given time in a fluid, the largest particles being deposited most rapidly. By this means the sand may be graded into different degrees of fineness of uniform size. When examined with a petrological microscope the quartz wedge described on page 209 is probably the quickest method of ascertain-

ing a knowledge of its crystalline composition, or when immersed in a suitable fluid its refractive index may be taken.

Refractive Indices (for D line) of Various Liquids and Cements

The visibility of objects illuminated by transmitted light, and their power of reflecting light when viewed by dark ground illumination, is greatly increased if they are immersed in a fluid or material of great difference in refractive index. The following table gives the approximate refractive indices for the line D of the spectrum for a number of fluids, cements, and solids.

Air	1
Water	1·33
Acetone	1·364
Ether	1·3566
Alcohol (ethyllic)	1·3638
Alcohol (absolute)	1·367
Acetic acid	1·372
½ Glycerine, ½ water	1·397
Fluor spar	1·433
Chloroform	1·446
Petroleum rock-oil	1·45
Glycerine	1·46–1·47
Quartz	1·46–1·55
Poppy oil	1·463
Paraffin liquid	1·47
Turpentine	1·472
Olive oil	1·476
Almond oil	1·478
Linseed oil	1·485
Castor oil	1·49
Toluene	1·495
Gum arabic	1·502
Benzine	1·503
Cedar-wood oil	1·51–1·52
Borax	1·515
Crown glass	1·5–1·55
Canada balsam	1·526
Clove oil	1·533
Creosote	1·538
Salt	1·542
Shellac	1·544
Phenol	1·549
Aniseed oil	1·55
Cinnamon ether	1·561
Horn	1·565
Flint glass	1·56–1·9
Cassia oil	1·578
Aniline	1·586
Metacinnameme	1·597
Quinidine	1·617
Cinnamon oil	1·6188
Carbon bisulphide	1·63

Styrax	1·63
Balsam of tolu	1·64
Monobromide of naphthalene	1·658
Piperine	1·68
Methelene-di-iodide	1·743
Sulphur in methyl-de-iodide	1·778
Phosphorus	2·093
Realgar	2·14–2·4
Diamond	2·417
Selenium	2·98

CHAPTER VII

NOTES ON TESTING MICROSCOPE OBJECT-GLASSES

Necessity of testing to a degree of accuracy beyond that demanded of the instrument—Not yet possible with microscope—Measurement of focal length —Aperture—Working distance—The Star test of the telescope—Spherical and chromatic aberrations—Star test applied to the microscope—Appearances of out-of-focus images—Test for zonal aberrations—Chromatic zonal aberrations—The Podura scale—The sine condition—Grayson's rulings—Test for contrast—Unstained bacteria—The Abbe test plate—Difference in focus for fine and coarse structure—Lenses that show diatoms best show all objects best if spurious resolution is avoided.

MANY methods of testing engineering instruments and machines are definite and satisfactory. Their errors can be measured to a much higher degree of accuracy than is required for the purpose for which they are to be used, and there is no difficulty in deciding whether a particular instrument is sufficiently perfect to accurately perform its work, while such errors as it may possess can be calibrated.

A screw that is required to measure to one-thousandth of an inch can be tested to a hundred-thousandth. The strength and qualities of materials can be measured to a degree of precision much greater than they are required to possess, and the results of such tests and measurements can be stated in actual figures. The mechanical adjustments of a microscope can be tested by the method described on page 166 with sufficient accuracy, but the optical testing of instruments has not yet been brought to this state of perfection.

In some cases an approach to such a condition has been made. A photographic lens, if it is to be used for taking pictures upon a chemical emulsion which consist of comparatively large grains of silver salts, need not produce an image which gives greater perfection than can be depicted on such a comparatively coarse grain. By means of a microscope the aberrations of a photographic lens can be measured to a degree of accuracy which is greater than can be depicted upon a photograph, and a statement of these errors can be expressed in terms that are sufficiently accurate to give some reliable information as to its suitability for the purpose for which it is required.

The testing of a photographic lens, however, is not simple. There are not one or two errors only, as in a screw, each of which has reference to a particular and different requirement. Fre-

quently the error in the pitch of the screw is all that is of importance. There are a number of errors in a photographic lens, all of which affect the same question, namely the production of a point-for-point image. When the image of a point is not a point it may be a disc due to diffraction, or it may be a disc or an irregular shape, due to either spherical or zonal aberration, chromatic aberration, spherical chromatic aberration, errors in centring, errors in workmanship, or the quality of the glass. Each of these errors may affect the perfection of every point in the image. The measurements of all these errors in a photographic lens, if considered in relation to each other, may give information as to what may be expected of its performance, but considerable knowledge and experience is required to form a correct opinion. All these errors can generally be reduced to small dimensions compared to the grain of a photographic emulsion, and a satisfactory test can be made which will decide if the outstanding errors are below a certain necessary standard.

With a microscope object-glass there is no means at present of measuring the errors and expressing them to a sufficiently accurate degree. An object-glass, used to show resolution of lines 120,000 to the inch, would require testing to a millionth of an inch, and even if this were possible great experience is necessary in ascertaining the relative influence of the different errors upon the final result. For instance, a small colour error is not generally so serious as zonal aberration, because for many purposes a colour screen can be used. On the other hand, when objects are to be recognised by their colour, the colour correction may be of primary importance. The effects produced in the final image by aberrations are often extremely difficult to distinguish from those produced by bad workmanship. A perfect microscope object-glass should have no errors, however small, and this is an impossibility. All that can be done is to endeavour to get rid of perceptible errors; but several such errors, indistinguishable separately, may add together and make a visible defect.

The result of this condition is that as far as the observer, apart from the maker, is concerned, the method of testing that has so far been adopted,* beyond the rough-and-ready method of resolving the structure of diatoms whose markings are of a particular fineness, has been the comparison of one object-glass with another.

Such comparisons are difficult to make, because the perfection of the image will depend quite as much on the nature of the illumination as upon the quality of the object-glass. It has already been pointed out to what a great extent the image is damaged when the object-glass is not evenly filled with light or when glare or flooding is present, and unless the conditions of illumination are approximately perfect no fair comparisons can be made.

Under certain bad conditions of illumination it is possible for an inferior lens to perform as well as a good one, and the performance of both to be so poor that the inferior lens may even be supposed to be the better of the two.

No satisfactory scheme of measurement of all the errors of the microscope object-glass can yet be laid down, but certain useful tests may be applied, the results of which should be taken in combination with the general performance of the lens on difficult test objects.

The numerical data as to focal length and aperture are generally of sufficient accuracy if taken from makers' catalogues, but every lens varies slightly and the following methods may be used to obtain greater accuracy.

The Focal Length.—The most convenient method of ascertaining this is by means of such an apparatus as the Beck micrometer eyepiece and a stage micrometer divided in portions of a millimetre. The Beck micrometer eyepiece consists of a scale of millimetre divisions below a positive Ramsden eyepiece, and if an image of the stage micrometer is thrown upon this scale before it reaches the eyepiece the magnification of the object-glass alone can be obtained. If an object-glass shows 1/10th of a millimetre equal to 1 millimetre on the scale, it magnifies ten, and this figure added to one and divided into the tube length gives its approximate focal length. The result is not strictly accurate, because the tube length is not the exact distance between the scale and the back equivalent plane of the object-glass (see page 34). A more accurate method is to ascertain the distance between the object (when in focus) and the scale of the micrometer eyepiece, and if that distance be called d, and the initial magnifying power of the object-glass m the focus F

$$F = \frac{d}{2 + m + 1/m}.$$

This equation is accurate, except that the distance between the two equivalent planes of the object-glass is included in the distance

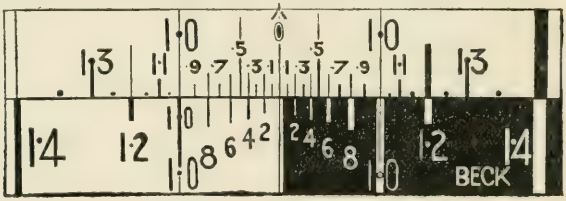


Fig. 90.—Apertometer.

(d), but it is generally so exceedingly small compared with the distance (d) that the result is not appreciably affected.

The Numerical Aperture.—The most accurate method of

taking the numerical aperture is by means of an apertometer. A simple form, costing only six shillings, consists of a rectangular glass plate, 3 × 1 inches and about $\frac{5}{8}$ inch thick. It has on its lower surface a scale of divisions marked with numerical apertures (see Fig. 90). If this be placed on the stage of the microscope so that the upper surface of the glass is in the focus of the object-glass and in the centre of the field an image of the divided scale will be formed near the back focal plane of the object-glass. To facilitate focussing a diatom is mounted on the upper surfaces. By removing the eyepiece of the microscope an image can be seen of a portion of the diagram shown in Fig. 90; or to obtain a larger image it can be examined by a low-power object-glass placed in the draw-tube of the microscope, in combination with an eyepiece, which converts the draw-tube itself into a microscope. When the draw-tube is slid into the position where the image is in focus the divisions that are seen at the margins of the field give the true numerical aperture.

This method of observing the image is not in all cases quite correct, as light enters the observing microscope from the object-glass which would not reach the eyepiece when the microscope is in use. The most accurate method of making the observation is not to use an object-glass in the draw-tube, but to use a low-power eyepiece in the microscope into which a disc with an aperture of about a millimetre has been inserted between the lenses. The image of the apertometer is then examined in the eyepoint of the eyepiece with a powerful magnifier.

For this and many other purposes a piece of apparatus called a super eyepiece carrier, which fits on the draw-tube of the microscope, is very useful. It consists of a sleeve which clamps on to the standard draw-tube, with an adjustable ring, carrying a high-power magnifier by means of which the eyepoint can be examined. The magnifier can be provided with a micrometer in its focus by means of which the diameter of the eyepoint can be measured. The apparatus also forms a convenient holder for an analysing prism or a tourmaline. With object-glasses of very low power the image of the apertometer is formed so far away from the back of the object-glass that it requires practice to estimate the exact point at which the margin of the lens cuts the aperture, but with powers higher than 16 mm. there is no difficulty.

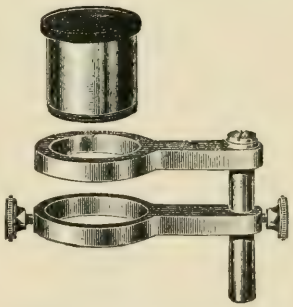


Fig. 91.—Super Eyepiece Carrier.

Another means of measuring the numerical aperture of

an object-glass is by measuring the size of the eyepoint with a particular eyepiece and a particular tube length, and by taking the exact magnifying power with the same eyepiece at the same tube length. The diameter of the eyepoint in millimetres (2Z) is equal to 500 times the numerical aperture divided by the magnifying power $\left(\text{see page 92. } 2Z = 500\,\frac{\text{N.A.}}{\text{M}}\right)$; the numerical aperture is the magnifying power divided by 500 and multiplied by the diameter of the eyepoint $\left(\text{N.A.} = \frac{\text{M}}{500}2Z\right)$.

The Working Distance, or the free distance from the front of the object-glass to the object, can be measured by carefully setting the object-glass so that it touches an uncovered object on a glass slip and then moving the body of the microscope back till the object is in focus, the amount of movement being measured for small distances by the graduations on the fine adjustment, or for larger distances by a depth gauge or micrometer, on the rack slide of the coarse adjustment. The working distance will vary slightly for different tube lengths and for different eyepieces; the shorter the tube length, the greater the working distance; and in general the lower power the eyepiece the greater will be the working distance also. The result obtained gives the working distance in air. This corresponds to about half as much again in glass. A lens that will focus through 1 mm. in air will focus through about $1\frac{1}{2}$ mm. in glass.

The numerical data of an object-glass give certain information as to the results that may be expected from it. By reference to the table on page 67 the theoretical resolving power corresponding with the numerical aperture may be obtained. From the focal length the degree of magnification that will be obtained with any particular tube length and eyepiece may be ascertained. From the working distance the suitability for particular work can be decided. But these data give no indication of the quality of the image.

The quality of the object-glass may be ascertained either by testing its various errors separately or by examination of special test objects to judge of its general performance. The most instructive method is no doubt to calibrate all the separate errors, as being the only way to make a really scientific comparison of different object-glasses. At present this cannot be done with the accuracy that is necessary, and even if it were possible it would be dangerous without a check upon difficult test objects of a similar character to those with which the object-glass is to be used.

The most useful all-round test object is a minute point of light on a black ground.

A star seen against a black sky through a telescope forms the most useful all-round test for a telescope. A star appears so

small that no telescope, however powerful, can show it as having any magnitude, and for practical purposes it may be considered to be a mathematical point. By examining how nearly its image, when accurately focussed, approaches to a point a rough impression can sometimes be formed of the quality of the telescope forming the image. Such light as does not come to the correct position in the image may sometimes be seen as a hazy margin or spread over some portion on the background, which should be jet black, but only large errors can be thus observed.

Such a general inspection will not give sufficient information, and it does not form an exacting test, the more so because the image produced by any instrument of a point, due to the effect of diffraction described on pages 73–76, is always a small disc, and a slight variation in the size of such a disc, due to lack of corrections or bad workmanship, cannot be detected. By examining the image of a point when it is out of focus a better test can, however, be made.

Suppose a lens to be uncorrected, the examination of a diagram (see Fig. 92) of the path of the rays of light as it forms an image of a point of light indicates that the image is not a point. In the case that is illustrated the rays from the edge of the lens meet the axis at a point nearer to the lens then those from the centre. The position where the smallest spot of light is formed is at *a*;

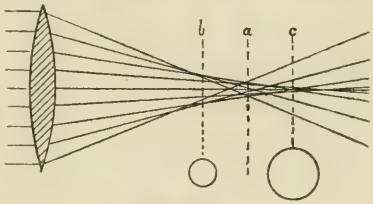


FIG. 92.

and if we examine the image at the position (*a*) by means of a low-power eyepiece it might not appear to be much more than a point. If, however, the bundle of rays be examined at two positions (*b* and *c*) on opposite sides of the best focus, the appearance in the two positions will be very different from each other. The diameter of the bundle is far smaller at *b* than it is at *c*; and as there is the same amount of light in both images the appearance at *b* will be a small brilliant disc with a sharp edge, and that at *c* will be a hazy indistinct disc, brighter in the centre but fading off in brightness towards the edge. The appearances differ in brightness, and also in the distribution of the light. It is brighter in the centre at *c* and it is brighter at the edge at *b*.

The examination of the image of a point of light at a small distance from the focus on each side, and careful comparison of the two images, forms a very delicate test of the spherical aberration, because it is only when all the rays are focussing to an exact point (modified by the diffraction effect, see page 73) that the appearance on both sides of the focus are identical.

The appearance of this out-of-focus image of a point is also a sensitive test of the workmanship of a lens. It must be well corrected for aberrations or the errors in corrections may obscure small defects in workmanship; but when that is the case the out-of-focus image will not be truly circular if any of the curves are not perfectly spherical. It may be irregular in shape or it may be elliptical. In the latter case the axis of the ellipse is generally in a different direction on opposite sides of the focus. Such an error is known by the name of "Twist," and is often not due to the curvature of the surfaces but to one of the lenses being under strain by unequal contraction in the cementing or by too tight mounting in a metal cell. The accuracy of centring can be tested by examination of the position of the rings, which should be concentric in or very near to the centre of the field. Imperfections in the homogeneity of the glass can often be detected by careful study of the out-of-focus image of a point.

This method can also be applied to test the colour correction. Suppose that Fig. 93 represents the cross section of a lens which has perfect correction for spherical aberration, but is uncorrected for colour, the blue rays represented by dotted lines coming to a focus nearer to the lens than the red. If the image be again examined on both sides of the focus at *b* and *c* the appearance at *b* will show a red fringe outside the disc, and the appearance at *c* will show a blue fringe at the margin; the interior portions of the discs have some light of all colours, which combine and form white light, but the presence of any colour fringe on the outside indicates an error in the colour correction. A comparison of the two images on each side of the true focus enables even faint traces of colour to be observed.

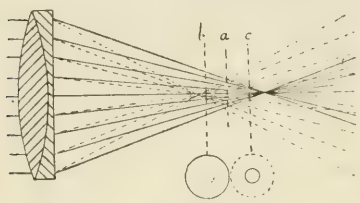


FIG. 93.

This method of testing lenses is called the Star test, and is far the most delicate direct test known. It enables errors to be seen, although it gives no measurement of the amount of such errors.

The application of this test to the microscope is not so easy as its application to the telescope, because of the difficulty of obtaining a small enough point of light of great intensity.

The most convenient means of producing a moderately small point suitable for the testing of low powers is by placing a small globule of mercury on a 3 × 1 inch vulcanite slip and striking the globule a smart blow with a flat strip of whalebone. This will break the globule into a number of minute spheres of mercury which appear like fine dust. If a small source of light be placed near this mercury dust, each sphere will reflect an image of the

source of light, which will be so small when reflected by the spheres of the smallest diameter that it is indistinguishable from a point of light with a low magnifying power. Smaller bubbles of mercury can be produced by chemical means, but they are only satisfactory for testing object-glasses intended for use on uncovered objects. Covering the mercury globules with a cover-glass or mounting them in fluid tends to distort their spherical shape and damage their reflecting powers. A more satisfactory method is to deposit a thin coating of silver on a cover-glass. It will be found that such a deposit is full of holes of all sizes, from those of a large size to some that are ultra-microscopic. Such a cover-glass can be mounted in any mounting fluid or examined dry. It must be illuminated by shining a very powerful light through it, preferably from a Pointolite or an arc lamp. The method of illumination, apart from the intensity, is of no consequence, as the diffraction at a very small aperture is so great that the light that emerges from it is in the form of a fan, as if the aperture were a radiant point.

Suppose that a brilliantly illuminated point is thus obtained, and that a microscope object-glass is to be tested by its means. In the first instance, light of only one colour should be used, either by the introduction of a colour screen or the use of a monochromatic source of light. If the lens is totally uncorrected, as in the old nonachromatic microscopes, or if the lens is only partially corrected, then, as indicated by the diagram Fig. 92, the appearances on either side of the focus will be totally different ; but even if the lens is well corrected it will probably be found on the first examination that the appearances on both sides are not the same, and this is because a lens can only be made correct for one position of its two conjugate foci—or, to put it in microscopic language, for one tube length—and the appearances on either side of the focus will only be approximately the same when the draw-tube of the microscope is extended to the exact position for which the object-glass is corrected. When this position is found, that will be the position where the best image will be formed by that object-glass. A variation in the thickness of the cover-glass has even greater influence than the tube length upon the corrections, with high-power lenses. The test is so delicate that if the test object be changed for a similar slide it is almost certain that the draw-tube will require to be readjusted, due to a small variation in the thickness of the cover-glass. If the colour of the light be changed there will be a change required in the draw-tube in all but the very finest apochromatic object-glasses. It is almost impossible to find any lens so perfectly corrected for colour that an error cannot be detected by this means. A lens is not always imperfect if it shows a small error, because the error may be smaller than the error introduced by diffraction, and it may not affect the perfection of the image.

The examination of the object-glass should be made with a high-power eyepiece magnifying from fifteen to twenty-five, so that the errors in the image may be magnified. The quality of the image will also depend upon the quality of the eye-piece and the latter should be of the type which it is intended to use with the object-glass which is being tested. The image on either side of the focus has been described as a disc; but when the object-glass is well corrected it is not a disc, but a series of rings with a bright centre, somewhat like the diffraction image figured on page 73. It is seldom that the rings appear exactly the same on both sides of the focus. Even at the best length of draw-tube there will almost always be errors in a wide-angle object-glass that will prevent such a condition, although the errors may be too small to affect the quality of the image, as the circles of confusion caused by such errors may all be inside the area of diffraction disc.

This method of testing requires great experience and must be checked by other tests. It is a perfect means of ascertaining the correct tube length. It shows whether the object-glass is reasonably well corrected. It shows by careful examination of the shape of the rings on either side of the focus whether there is any serious error in workmanship. If the surfaces are not truly spherical the rings will not be circular. It shows any serious error in centring, but it does not show the zonal aberration and only to a limited extent the correction of the sine condition.

If, however, a series of diaphragms are used behind the object-glass a stage further can be reached in the test, and here we can obtain certain numerical data.

Let it be assumed that Fig. 94 represents a lens system which is well corrected for spherical aberration, but possesses certain errors in the zonal corrections. The rays A and C meet at the same point on the axis, but those at B and D meet the axis at different points. The tube length of the microscope having been set for the best general effect, the appearances of focussing slightly on one side or the other of the focus may be so nearly the same that it would appear to be thoroughly well corrected. In the Star test of the lens as a whole the errors due to the rays B and D may tend to neutralise each other, and may not affect the general appearance of the out-of-focus discs of light.

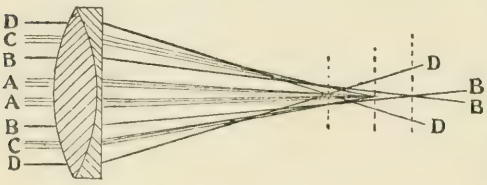


Fig. 94.

This error of the spherical aberration in intermediate zones of the lens is called zonal aberrations. It can be tested in the following manner. If behind the object-glass an adapter (Fig. 95)

be screwed into the microscope, which carries a sliding tray with cells, thin metal discs with apertures and glass discs with

Fig. 95.—Post Object-glass Diaphragm Holder.

central opaque patches may be placed in the sliding tray, and combinations of these rings and patches of suitable sizes enable the light from all except definite zones of the object-glass to be excluded.

It is convenient to divide an object-glass into four zones, one in which a disc with a small aperture cuts out all but the portion *a*, Fig. 94. The next with an opaque disc of a diameter equal to *a a* and a ring of the diameter *b b*, and so on, and a separate Star test can then be made of each zone of the object-glass. By altering the tube length the aberration of a lens is altered, and if the error is not too great a tube length can be found at which the appearance on either side of the focus is approximately the same. The amount that the tube length is altered for each zone, although it does not give a direct measurement of the aberration, gives a measurement which when carefully studied indicates the character and the amount of the error. When all the zones are correct at the same tube length the lens is perfect for zonal aberration. Great care and very close observation is required to obtain accurate setting of the tube length in consequence of the small bundles of light which are being dealt with, and monochromatic light must be used to obtain reliable results. By taking readings with four colour screens or four lines in the spectrum the variation of the spherical aberration for different colours is obtained. As high a power eyepiece as will give the necessary light should be used, and the same eyepiece should be employed for all comparative tests. It is essential that the point aperture which is used should be placed in the centre of the field of view, because, as the diaphragms which are limiting the zone being tested are situated at a distance behind the lenses of the object-glass, the light must come centrally through the object-glass, or the zone that is being examined may not be correctly selected. A very brilliant illumination is necessary, because the aperture in the silver film which forms the object must be so small that its shape cannot be recognised, and the use of the diaphragms behind the lens still further reduces the light that reaches the image. A Pointolite or an arc lamp is the best illuminant ; if the light is not sufficiently intense the aperture of the object-glass may be subdivided into three instead of four zones ;

and the setting of the central zone is sometimes rendered less difficult if a square instead of a circular aperture is used. The curious star-shaped diffraction image which a square aperture creates is somewhat easier to set for equality of appearance on the two sides of the focus.

The scale of a Podura (Lepidocyrtis curvicollis) has long been used as a test in this country for object-glasses of shorter focus than 1/2 inch (12 mm.). It has a structure which gives the appearance of a series of regularly arranged quills with a black margin and a white centre—what that structure actually is has not been determined. The characteristic appearance is probably due to corrugations on both sides of the scale. It forms the most sensitive test for tube length that has yet been met with. There is only one exact tube length which gives the same appearance on both sides of the focus with a cover-glass of a definite thickness. Comparing this tube length with the tube length setting obtained with a Star test it corresponds with the tube length setting of the central zone and not with the tube length setting of the whole aperture unless the zonal aberrations are perfectly corrected. The image of the Podura scale is always far more brilliant and better defined when the zonal corrections of a lens are perfect, but the setting is not affected by the errors in the outer zones. It is a test of the greatest value to the experienced optician, but requires to be studied with lenses which have known defects in order to appreciate its advantages. The appearance of the image will then reveal errors in centring, errors in workmanship, and many of the errors on the aberrations. It should be examined with a comparatively small cone of illuminating light. The regular periodic structure emits so large an amount of diffracted light that all parts of the aperture of the object-glass are filled with a large amount of light, although it is not evenly distributed.

The foregoing tests have all been concerned with the bundle of light which enters the microscope from the central point in the field of view and passes to the central point in the image. They have no reference to the performance of the lens in any portion of the field of view except the exact centre. The question of the perfection of the image at the edge of the field, or the flatness of the field of view, calls for totally different consideration, but the definition of the image of an object, even in the centre of the field of view, requires a further test, because it would be possible to make a lens which would give a perfect image of a single point in the centre of the field which would be a bad image of any object that had a finite size. The sine condition explained on page 43 must be correct, or different portions of a lens may be giving different magnifications, and even a small object in the middle of the field might consist of, say, three images of different sizes on top of one another. Suppose A, Fig. 96, repre-

FIG. 96.

sents the outline of an object depicted by the outer edge of such a lens, B the outline depicted by the middle, and C the outline depicted by the centre of the lens, there is an infinitely small point in the centre that is sharp, but all other portions of such an object will be indistinct. This can be tested by moving the point being examined slightly to either side from the centre of the field; then, if the sine condition is not correct the point will appear somewhat like a comet when refocussed to it.

A great deal has been written on the testing of lenses by means of particular test objects. Such tests are valuable in comparing one object-glass with another. They seldom give results that convey much information taken by themselves. A series of ruled lines, such as Grayson's rulings, however, are useful as they indicate what degree of fineness of detail can be resolved by a particular object-glass.

The Grayson's rulings are the most perfect fine rulings that have yet been made. They were ruled by the late Mr. H. J. Grayson, of Melbourne University, who invented the method. They are now being ruled by Messrs. Lyle and Merfield, who are continuing his work at the same University.

They are made in three forms. The coarsest has ten rulings on one slide and the other two twelve rulings on one slide, as follows :—

No. 1.	No. 2.	No. 3.
1,000 lines to the inch	5,000 lines to the inch	10,000 lines to the inch.
2,000 ,, ,,	10,000 ,, ,,	20,000 ,, ,,
3,000 ,, ,,	15,000 ,, ,,	30,000 ,, ,,
4,000 ,, ,,	20,000 ,, ,,	40,000 ,, ,,
5,000 ,, ,,	25,000 ,, ,,	50,000 ,, ,,
6,000 ,, ,,	30,000 ,, ,,	60,000 ,, ,,
7,000 ,, ,,	35,000 ,, ,,	70,000 ,, ,,
8,000 ,, ,,	40,000 ,, ,,	80,000 ,, ,,
9,000 ,, ,,	45,000 ,, ,,	90,000 ,, ,,
10,000 ,, ,,	50,000 ,, ,,	100,000 ,, ,,
	55,000 ,, ,,	110,000 ,, ,,
	60,000 ,, ,,	120,000 ,, ,,

They are mounted in realgar, and are wonderfully regular and clean lines.

The table on page 67 indicates the theoretical limit of resolution of an object-glass of a particular numerical aperture, and tests on a Grayson ruling will determine how nearly an object-glass reaches its theoretical limit in practice. Great care must be taken to ensure that the light is perfectly centred, and a cone of illuminating light must be used which fills the whole aperture of the object-glass evenly with light. If this is not the case spurious diffraction images may be obtained which are not true

resolution (see page 80). Such images may give the appearance of ruled lines which would not be visible if the lines were placed at a different angle or in a different position as regards the illumination. For this test it is absolutely essential to remove all glare (see page 111), and a very small portion of the field only should be illuminated.

If an object-glass which has a numerical aperture of ·35 N.A. will resolve rulings 35,000 to the inch when they are placed in any direction on the stage of the microscope, it is probably almost perfect in its corrections. If in addition to this no zonal errors can be distinguished on the Star test previously described, and the colour aberrations on this test are good, it will probably perform perfectly on any object. It should, however, be examined on a very faint test, such as a diatom mounted in Canada balsam, to see whether the image is veiled over by any outstanding aberration. This test also must be absolutely free from glare.

The markings of diatoms have been largely used as tests, and are extremely useful if great care be taken to avoid spurious resolution (page 83) and glare (page 111). The results must not be altogether relied upon unless the fineness of the markings of the diatom examined are measured, because individual specimens vary in the fineness of their markings to a limited but quite important extent.

Probably the best test that can be found as a comparsion test for a high-power object-glass of an aperture not above 1·2 N.A. is an unstained specimen of bacteria, viewed under dark ground illumination. Such a specimen may be made from the mouth, and can be permanently mounted in a drop of water to which a little formalin has been added.

This object cannot be used for object-glasses of a larger aperture than 1·2 N.A., because no larger aperture lens can be used with most dark-ground illuminators. One of the great advantages of such a test is that the best tube length can be easily ascertained, and any mist around the specimen is almost certain to be due to aberration errors. A single small object, or a few only, in the centre of the field should, however, be used, or the glare from materials near the object being examined (see page 123) may injure the clearness of definition.

Stained specimens vary according to the strength of the stain, and as the stain is liable to fade cannot be relied upon to remain constant.

In the opinion of the author, the Abbe test plate is not a satisfactory test for spherical and zonal aberrations when used in the manner recommended with oblique light thrown upon the object by stops below the substage condenser. A beam of light thrown from below upon an object of this nature, when it has passed the object has been spread out by diffraction at the object into a much larger beam, and it cannot be assumed that a specified

portion of the object-glass aperture is being tested. The image is being formed by a larger portion than is supposed, and it is difficult to say what the portion is that is being employed. The results obtained by this test are misleading, and frequently do not correspond with the performance of the object-glass on other test objects. The only satisfactory manner to test the various zones of an object-glass is by means of stops behind the object-glass itself.

Those who are accustomed to test microscope objects on diatoms have noticed that with some lenses the best image of the fine structure of a diatom is not at the same focus as the best image of the coarse outline, and that a distinct change of the focussing adjustment must be made to see first one and then the other clearly. By altering the tube length the two images can often be rendered sharp at the same position. If the fine structure is sharp above the focus of the coarse structure the tube length requires to be shortened, and vice versa. It will generally be found that the length of tube which gives the two images in the same plane is the same length that is required to give the best average correction for the object-glass in use when tested on the Star test. This phenomenon has given rise to the idea that the image of fine structure is formed by a portion only of the oblique rays of light which form the image, and that the correction of these rays alone is all that is required to ensure a perfect image of objects of a particular degree of fineness, and that a special set of rays, with a particular degree of obliquity, is being used out of the whole bundle which enters the object-glass to depict each degree of fineness of structure. This idea is a misconception.

The phenomenon is due to spherical aberration, and shows that the lens is either not being used at its correct tube length or is imperfectly corrected. If an entirely uncorrected lens is used to throw an image upon a screen it will be found that the image will not be sharp at any position of the focus, but that the best general appearance of an exceedingly fine object is at a different focus to that of a large one.

The experiment can be tried by projecting, with a bull's eye lens, the image of a fine slit upon a screen, and then opening the slit to a considerable size. Monochromatic light must be used to overcome the colour aberrations of the bull's-eye.

The appearance of the fine structure at a different focus to that of the coarse outline is only an indication that the lens has not its spherical aberration perfectly corrected, and the correction of this, by altering the tube length or some other means, will improve the definition both of the fine structure and of the coarse outline. Any error in correction will damage to a greater or less degree every class of object seen through a lens, whether it be small or large, although a lack of sharpness will be more easily detected on a small object.

From an incorrect interpretation of this phenomenon, and from the fact that spurious resolution of periodic structure can be obtained by bad lenses, it has been assumed that object-glasses that are good for resolving diatoms are often inferior for general work. If care is taken in testing lenses to avoid spurious resolution it will always be found that the best lenses for resolving diatoms are the best for all other kinds of work.

This form of misconception has also led to the belief that lenses with a large numerical aperture are not so serviceable for general work.

It is true that the aberrations of a wide-angle lens are not so easy to correct as those of smaller aperture, but if the quality of the corrections is the same the wider angle lens is better for all kinds of work. If there are any errors in a lens they will tend to injure the sharpness of an image; each ray that does not proceed to its appointed spot goes to some other portion of the image and produces a tendency to haziness, and therefore it is not wise to make a lens that has an aperture so large that it will give a degree of unnecessary resolution: greater than could be required with the highest-power eyepiece that will be used with it. The best lenses are now made, however, with such perfect corrections that it is frequently useful to use an eyepiece magnifying twenty-five and sometimes even fifty diameters, and wide-angle lenses, especially for high powers, are becoming more universally used.

A 4 mm. object-glass with a very high-power eyepiece may, for instance, be required in cases where circumstances preclude the use of an immersion fluid. In such a case it should possess the largest possible numerical aperture.

The foregoing notes on testing microscopic lenses are not intended to embody a complete or even a satisfactory means of ascertaining the quality of an object-glass.

It is to be hoped that methods will be devised which will enable all the errors of a lens to be stated in figures and to a degree of fineness beyond the accuracy that is required in the use of the instrument itself.

Further research is required before this can be done. Such research is already commenced, and shows hopeful signs; in the meantime the above description of tests now in use may prevent wrong conclusions from being drawn by inexperienced observers.

CHAPTER VIII

MICROSCOPES FOR SPECIAL PURPOSES

Microscopes for measuring—Scales in eyepiece—Filar micrometer—Brinell test microscope—Projection measuring microscope for wire and fibre—Micrometer microscope—Stage micrometer—Tutton interferometer microscope—Screw measuring microscope—Barnard interferometer plates—Research microscopes—The "Radial Research"—Research outfit—Greenough binocular microscope—Ultra microscope—Process microscope—Museum microscope—Projection microscope—Horizontal reading microscope—Tank microscope—Dissecting microscopes—Demonstration microscope—Sand and dust microscope—Field mining microscope.

THE standard form of microscope has been described in *The Simple Handbook*, but there are a large number of purposes for which a microscope is required which call for special instruments. This chapter describes such instruments while a later chapter is devoted to Petrological apparatus.

Microscopes for Measurement.—Very minute objects can be measured in an ordinary microscope by inserting a glass plate with a ruled scale of divisions in the focus of the eyepiece. The value of each division of the scale under the particular magnification in use is determined by placing upon the stage of the microscope a stage micrometre. This is a glass plate ruled with fine divisions, such as 1/100th and 1/1,000th of an inch, or 1/10 and 1/100 millimeter. A Grayson ruling is made with 10 sets of rulings, 1,000, 2,000, 3,000, up to 10,000 to the inch, which is useful for very high magnifying powers. Considerable accuracy can be obtained if the draw-tube of the microscope be moved in and out until a certain number of divisions in the eyepiece exactly correspond to one division in the stage micrometer. The value of each division of the eyepiece scale having been ascertained with a particular object-glass, and the draw-tube drawn out to the ascertained distance, the object to be measured is placed on the stage of the microscope and the eyepiece scale will be seen superimposed upon it.

The field of view of a microscope is somewhat curved and slightly distorts the image. A measurement taken in this manner may be slightly incorrect if the object measured occupies a large area of the field unless the eyepiece scale is adjusted to the stage micrometer, using lines that occupy about the same positions as the margin of the object being measured.

For measuring small objects, this method of measurement is very convenient and accurate, and a traversing micrometer eyepiece enables great delicacy of measurement to be employed. This is called either a cobweb micrometer or a Filar micrometer. It consists of a positive eyepiece in the focus of which is one fixed cobweb and a second cobweb which is carried by a slide which can be travelled across the field by means of a micrometer screw. This screw has a graduated drum to read the amount of the travel. In the field of view is a saw-shaped edge, each tooth of which corresponds to a complete turn of the screw (Fig. 98). Such eyepieces are sometimes provided with two movable cobwebs instead of a fixed and a movable one.

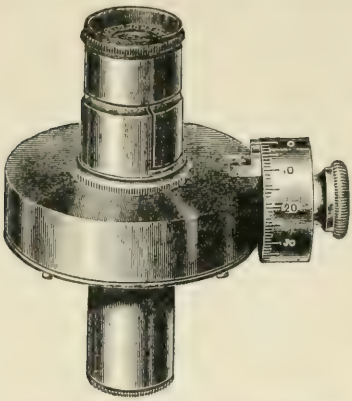


Fig. 97.—A Cobweb Micrometer.

The best form of such a micrometer is one which has a screw with a millimetre pitch and a drum divided into 100 parts; each division then reads 1/100th of a millimetre. If an object-glass, 16 mm. focus, is used the tube length of the microscope can be adjusted until it magnifies exactly 10 diameters, and each division then represents 1/1,000th of a millimetre (μ) on the object.

Fig. 98.

If a 1/12th inch oil immersion object-glass is used and the tube length slightly extended a magnification of 100 will be obtained, and the divisions then represent 1/10,000th of a millimetre (1/10μ). The power of the positive eyepiece used to view the cobwebs is not a matter of great importance: it should have a power of from 8 to 10.

This form of measurement is only of use for objects small enough to be included in the field of view of the microscope. They should, in fact, not exceed about 1/2 the field in length.

Fig. 99.—Brinell Test Microscope.

A small and convenient microscope is made for measuring Brinell tests. It has a scale in the eyepiece, each division of which represents 1/10 mm. on the object. The Brinell test consists of dropping a steel ball upon a metal plate and measuring the

size of the indentation which it makes by its impact with the metal.

Various simple microscopes of this kind are made for rapid measurement. The magnifying power and the size of the field of view can be modified to a certain extent according to the size of object which it is desired to measure.

The human eye can distinguish, under the most favourable conditions, two objects as being separate if they are separated by an amount which subtends about 1/2 a minute of arc, equal to about $1\frac{1}{2}$ thousandth of an inch, placed 10 inches from the eye. Such an observation will, however, be found to be somewhat of a strain under ordinary conditions: such objects at a distance

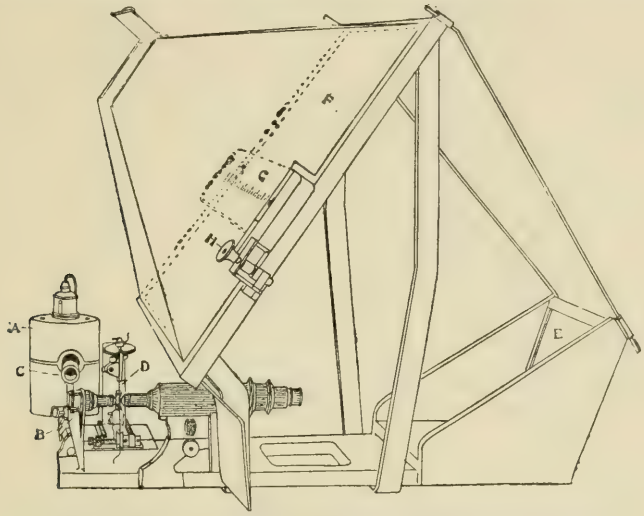


Fig. 100.—Patent Lewbeck Projection Measuring Microscope. Light-excluding curtains are removed.

of 10 inches from the eye should, apart from comfortable resolution, not be less than 1/250th of an inch (·1 mm). If an observer is setting a line to the edge of an object in order to measure its length, the error that may arise from incorrectly setting his scale or cobweb micrometer will not exceed this amount. If the scale of the cobweb is examined during the process with an eyepiece magnifying 10 diameters, the error in setting is reduced to 1/2,500 inch (·01 mm.); if the object is magnified 10 diameters by the microscope this error represents on the object only 1/25,000th of an inch (·001 mm.); thus the microscope forms a very perfect method of measurement in as far as the question of making the observation is concerned. Quite a rough setting will not have any setting error that is large enough to be of consequence except in the most delicate operations.

For rapid measurements the system of projecting the image formed by the microscope upon a ground-glass screen is extremely convenient, and for the measurement of objects so small that they would be crushed or distorted by contact measurement such a system is invaluable. Figs. 100 and 101 show a patented measuring microscope known as The Lewbeck, designed by R. and J. Beck, Ltd., for the London Electric Wire Co. and Smiths Ltd., for the measurement of wire, fibre threads, or any similar material. A is a powerful light, preferably a Pointolite lamp, fixed about 8 or 9 inches to the left of the microscope. A powerful beam of light is thrown by means of a lens (C) and a prism (B) through an achromatic substage condenser upon the thread (D) being examined. An apochromatic 8 mm. object-glass and a compensating eyepiece project an image of this thread by means of a mirror (E) upon a ground-glass screen (F). The magnification of the instrument is exactly 1,000 diameters; by using a second eyepiece exactly 500; or if the eyepiece is removed and the object refocussed exactly 100. On the observer's side of the ground glass, and almost in contact with it, is a glass scale divided in tenths of an inch. This can be moved horizontally across the image by means of a rack and pinion and the measurement made in 10,000ths of an inch, or by estimation to about 1/50,000th of an inch. A special holder for the wire enables it to be rapidly attached and brought to exact position in two V-shaped guides, and in actual practice it is found that measurements can be regularly made at the rate of two or three a minute. In order to shield the ground glass from light, it is enclosed by a wooden hood with an observing aperture about 6 inches × 3 inches, and the whole of the back portion of the apparatus is enclosed by curtains (not shown in figure). The microscope and all attachments are fixed upon an iron base, and no adjustment for focussing except a fine adjustment is provided, so that when once set it cannot be interfered

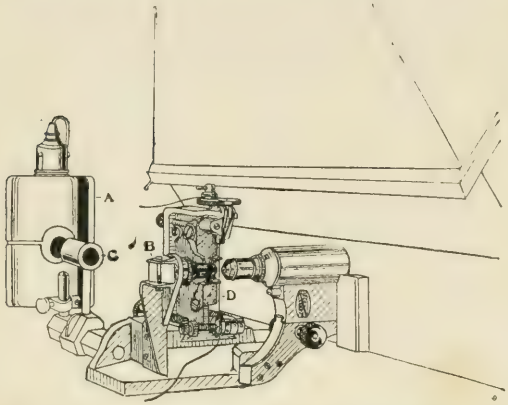


FIG. 101.—Patent Lewbeck Projection Measuring Microscope, showing wire holder.

with. The object holder can be adjusted in all directions and the thread can be revolved 90 degrees, so as to measure it in two meridians. The holder can be moved forward, bringing an ordinary microscope stage into position on which a reference stage micrometer may be placed.

The same instrument can be used for measuring and examining powders, grains, small screw threads, and engineering units. With the high magnification employed it has only a small field of view, but an object-glass with a lower magnifying power and a larger field can be substituted for the measurement by projection of larger material.

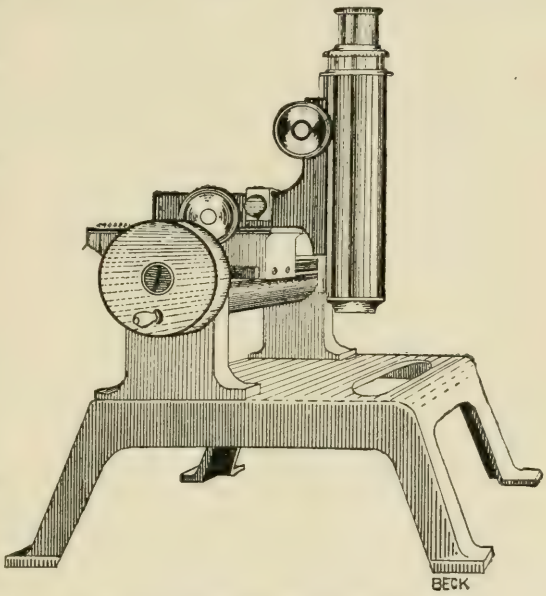


FIG. 102.—Micrometer Microscope.

When it is required to measure a large object with the accuracy that is obtained with a microscope on a small object, it can be best done by a travelling microscope. A wire or cobweb is fixed in the eyepiece of the microscope and the whole microscope is moved by means of a micrometer screw. Fig. 102 shows a micrometer microscope in which the microscope body has a rack-and-pinion focussing adjustment and a draw-tube. The object to be examined is placed on the stage, and the whole body travels along a horizontal slide moved by a micrometer screw which is generally made of a pitch of 1 mm., the drum being divided into 100 divisions, each of which moves the instrument ·01 mm. Objects up to 4 inches in length can be measured by this instrument. A finer pitch screw can be provided and a drum with a larger number of divisions if it is desired to have a finer reading. The microscope is also provided with a cross motion actuated by a rack and pinion with a scale reading to ·1 mm. This micrometer microscope is so made that it can be stood upon its end, so that the microscope

is horizontal and the main slide vertical. By this means vertical measurements can be made, and if a telescope object-glass be screwed into the nosepiece of the microscope instead of the microscope object-glass, it can be used as a cathetometer, or reading telescope, for measuring scales at a distance.

In many of the instruments used for measuring lengths, microscopes are attached to a moving slide for accurate readings of length. They are sometimes provided with cross wires, but more frequently with a cobweb micrometer (Fig. 97) by means of which small distances can also be measured.

A special microscope can be made for micrometric work with an eyepiece of such a nature that the magnifying power of the microscope can be varied without any alteration in the focussing adjustment. This is useful for certain micrometric purposes, as it facilitates the means of setting the eyepiece scale rapidly to exactly agree with divisions on a scale on the stage of the microscope. It is not often used, as it is a very expensive and elaborate eyepiece.

In all the above methods of measurements, the results depend for their accuracy on the correctness of the rulings of a stage micrometer which form the standard of comparison, or upon the freedom from error of a micrometer screw. Up to the present time no stage micrometer has been actually calibrated, although very careful comparisons have been made as to the regularity of the spacing of different makes of micrometers.

Dr. A. E. Tutton designed in 1909 a comparator (*Phil. Trans. of the Royal Society*, Series A, vol. 210, pp. 1–34) for calibrating the standard yard, in which the measurements are made in wave lengths of light. Fig. 103 shows a general arrangement of the apparatus. Two microscopes, of which one only is shown, can be travelled along a solid bed, and each microscope carries an optically flat mirror on one side which is parallel to an optically flat glass plate carried on the fixed bed of the instrument. This converts each microscope into a Fabry and Perrot interferometer, and suitable observing apparatus is provided to examine the movements of the interference bands as the microscope is travelled along the slide. The number of bands, one of which corresponds to a wave length of some monochromatic light such as that of cadmium, can be counted as they pass a cross wire when the microscope is moved towards or away from the fixed reflecting plate on the bed. By the use of cadmium light these bands can be observed even when the microscope mirror has moved several inches from the fixed reflector, but the labour of counting such a large number of bands as are contained in a long distance has been obviated by a method of step-by-step measurement with two microscopes in slides that can be moved either separately or together.

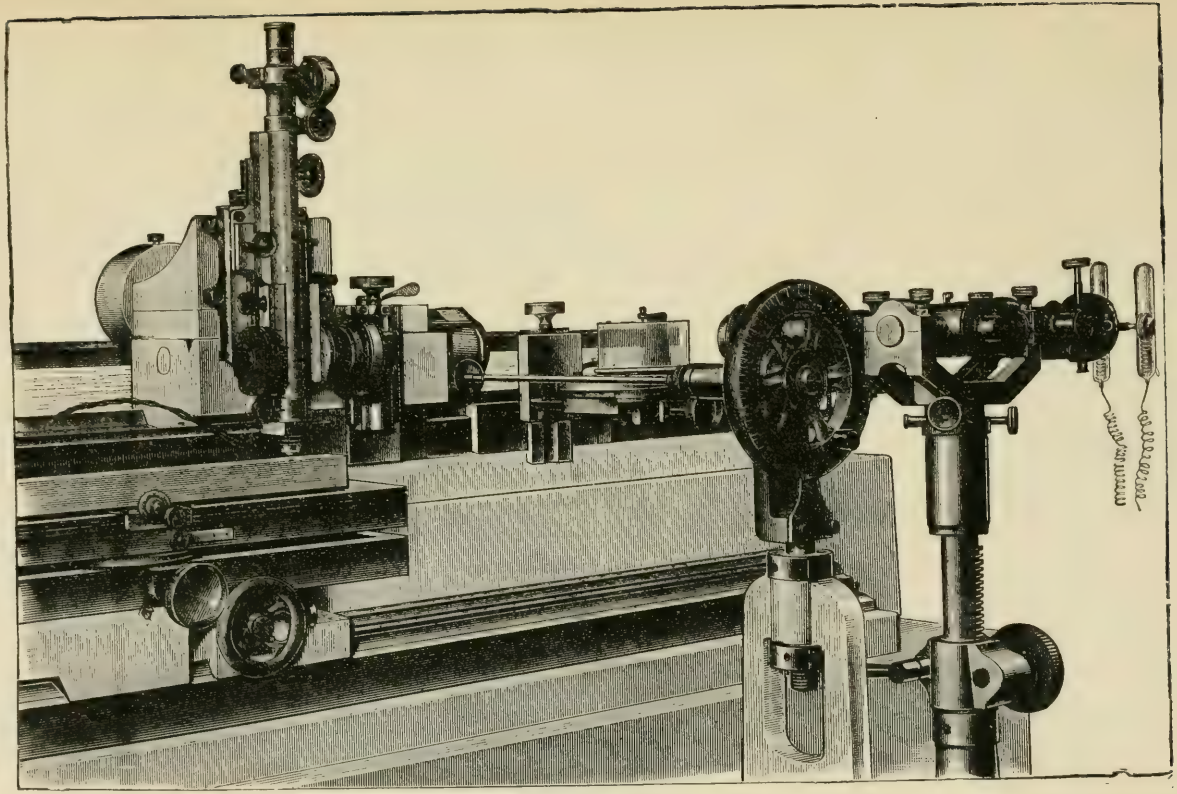


Fig. 103.—Dr. Tutton's Interferometer Microscope Micrometer.

The microscopes used in this form of instrument consist of a body provided with very rigid and perfect focussing adjustments, and a black glass mirror with delicate tilting adjustments for placing its surface absolutely parallel with the fixed reflector. It has a cobweb eyepiece micrometer and high- and low-power object-glasses. For the most delicate measurements Dr. Tutton employed as index marks on the object to be measured five extremely fine lines 1/40,000th inch apart, ruled on glass, and used a magnifying power of about 1,500 diameters. The cobweb micrometer was so set that the two lines were about the same distance apart as the image of the ruled lines, and they were then set so that they were on each side of the central line of the five.

The ruled lines were ruled by Mr. Grayson of Melbourne. The glass on which they were ruled was in some cases silvered, but they were all illuminated with top light by means of a thin glass vertical illuminator.

Such an instrument as this, which is now under the charge of the National Physical Laboratory at the Board of Trade Standards Office, is capable of calibrating all the errors of a stage micrometer to a degree of accuracy far greater than is required for ordinary work, but which is required for certain scientific purposes. The mechanical slides and bed were made by Troughton & Simms, and the microscopes and interferometer mirrors by R. & J. Beck, Ltd. The high power used in the original instrument was a dry 1/14 achromatic, but at the suggestion of the author a 4 mm. Beck apochromatic, with a higher-power eyepiece, has been employed on a second instrument constructed for Dr. Tutton. It gives superior results, due to its more perfect corrections, and has a larger aperture.

Small microscopes are frequently attached to measuring instruments for reading scales to a finer degree of accuracy than the scale would otherwise permit of. They generally consist of a low-power microscope with a scale in the focus of the eyepiece, so arranged that each division represents 1/10th or 1/20th of a division on the primary scale, and are frequently provided with a transparent thin glass illuminator to throw a beam of light through the object-glass upon the scale. They are specially constructed to suit the particular instrument with which they are to be used.

A form of microscope (Fig. 104) is made by J. Swift & Son, Ltd., for the measurement of screw threads and small rods or wires, in which the object is moved by micrometer screws instead of the microscope. This is very convenient for particular purposes. It is designed to give the length and pitch of a screw to ·001 mm.; the maximum, minimum, and effective diameter to ·01 mm.; and the angle of the thread to 5′. The object is held either between centres or on a chuck fixed to the movable upper

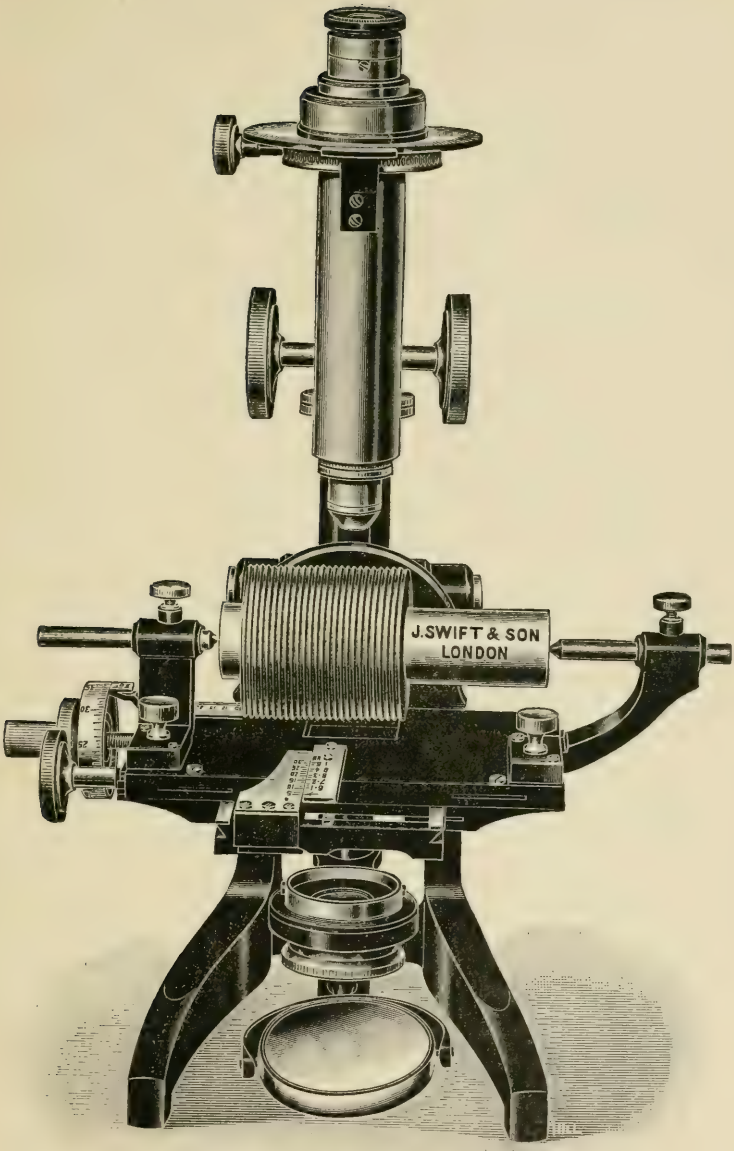


Fig. 104.—Screw Measuring Microscope.

stage and is measured by moving it across the field of view by a micrometer screw with a drum which reads by a vernier to ·001 mm.; the movable stage plate is held against the point of the micrometer screw by springs. The width of the object is read on a scale with vernier reading to ·01 mm. The angle between two lines, edges, sides, etc., is ascertained by rotating the eyepiece, which has cross lines in the focus of the top lens, by means of a tangent screw, and the angle of rotation is read on a divided circle with a vernier to 5′. The entire stage can be inclined on a horizontal axis at right angles to the optic axis by means of a tangent screw, and can be set on a divided scale and vernier to 5′. When the pitch of a screw is being measured the stage should be inclined to the same number of degrees as the angle at which the thread crosses it. This can first be measured by the rotation of the eyepiece. The fine adjustment milled head is divided to read to ·01 mm. for measuring depth and for obtaining the correct position for viewing the profile of a screw thread. The aperture in the stage is arranged to hold a sheet of glass upon which minute or flat objects may be placed. Special adjustable arms are supplied which hold adjustable male and female centres. The horizontal travel is 28 mm., but by resetting the object considerably longer objects can be measured.

A special appliance (Fig. 105) for measuring the accuracy of the adjustments and rigidity of a microscope has been devised by Mr. J. E. Barnard, which consists of a pair of transparent interferometer plates of the type used in Dr. Tutton's measuring microscope, but employed in a novel manner. One of these transparent glass reflecting plates, mounted in a metal holder, is attached to the nosepiece of the microscope, as if it were an object-glass; the other is placed upon the stage of the microscope, mounted on a plate that can be levelled by three screws. The two plates can then be set so that they are exactly parallel, and in use they are approached to each other until they almost touch. If light is thrown down through the plates by means of a vertical illuminator then by removing the eyepiece of the microscope and looking down the tube, interference bands or rings will be seen, caused by the interference of the light reflected between the two parallel plates.

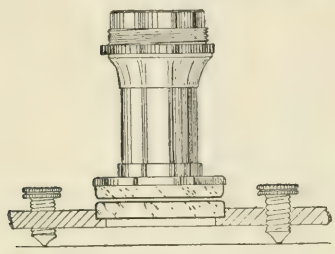


Fig. 105.—Barnard Interferometer Plates, for testing.

A better view of them is obtained by using a low-power object-glass at one end and an eyepiece at the other end of the draw-tube, thus converting it into a low-power microscope; and if cross

wires are used in the focus of the eyepiece, any movement of the interference bands can be accurately observed. A special combination of lenses to drop into the draw-tube of the microscope like an eyepiece is made for those who have not a suitable object-glass or means of attaching one.

It is better to use monochromatic light for the observation; an Osglim lamp or a sodium flame are simple methods of obtaining such a light.

One of the interference plates is reversible; it is truly flat on one side, which gives straight bands, and very slightly curved on the other, which gives circular bands.

The movement of the bands across the cross wires indicates a movement between the body and the stage of the microscope. If the image of the interference bands is displaced by the amount of one band, it represents a movement of about 1/100,000th of an inch, and about one-tenth of this amount can be detected. The use of this apparatus demonstrates that a microscope never has been and probably never can be made that will hold its position against considerable pressure of the fingers on the various parts, as the flexure and elasticity of all metals is sufficient to be readily observed. The Massive and the Radial Research microscopes, however, show a rigidity that has probably not been attained before. The quality of the adjustments, both as regards back lash, side play, and regularity of movement, can be tested and expressed in accurate terms. The results of such defects can be observed, apart from the movements caused by the flexure of the instrument, and can be stated independently. The appliance also shows whether external vibration moves a microscope as a complete unit without affecting the adjustment of its parts.

Research Microscopes.—In *The Microscope, a Simple Handbook*, a research microscope, "The Massive," designed especially for medical and bacteriological work, is described. For those purposes it is probably the best instrument yet produced, but there are certain purposes for which the microscope is used that require adjustments not provided in the Massive microscope.

The Radial Research microscope (Figs. 106 to 112) has been designed to supply these deficiencies, and to do so without dispensing with the great rigidity of the Massive model.

For metallurgical work and for the examination of other opaque materials a vertical illuminator is used for throwing the light through the object-glass upon the specimen (see *The Microscope, a Simple Handbook*). This illuminator fits on to the body of the microscope behind the object-glass, and when the lamp, often on an optical bench, has been arranged to direct a beam of light upon the illuminator, any movement of the body, for altering the focus for objects of different thickness or for focussing object-glasses of different powers, would upset the illumination. For such work a focussing adjustment to the stage is necessary,

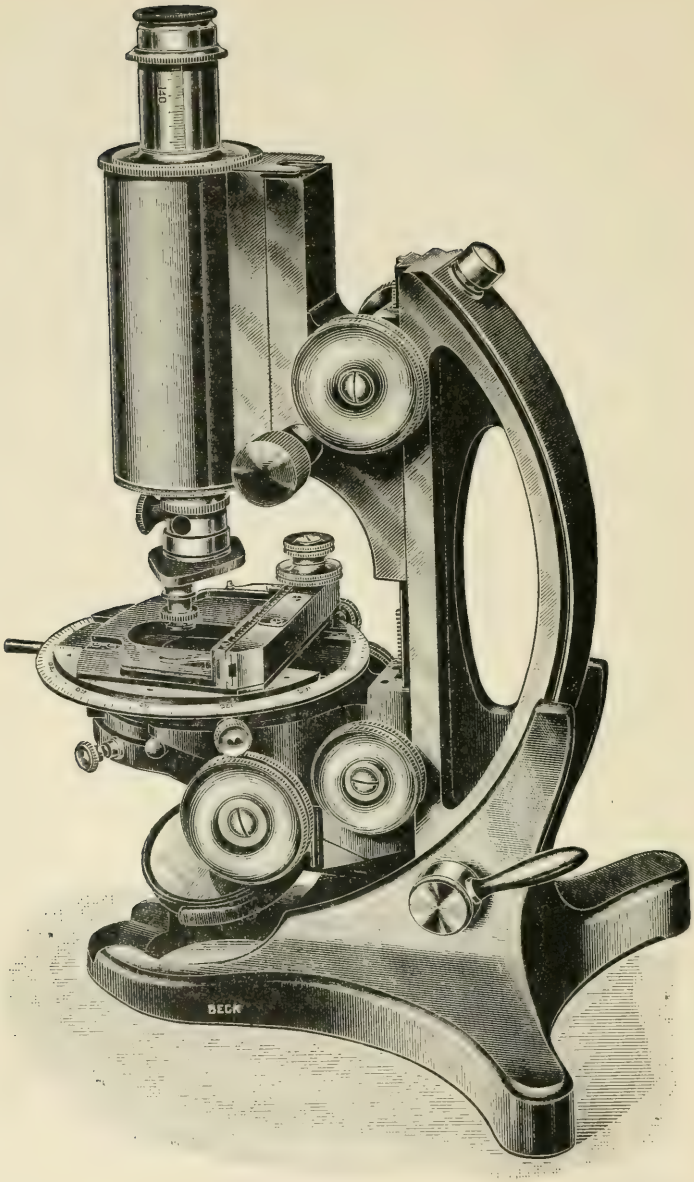


FIG. 106.—Radial Research Microscope. Regular model—circular stage.

so that different objects can be examined without moving the body of the microscope. The small motion involved in the use of the fine adjustment is not of any consequence; and as no satisfactory slow motion has yet been applied to a stage that did not restrict its use for other purposes the fine adjustment is left on the limb of the microscope.

For the use of the Ultra microscope also a focussing stage is required, so that the fine feather of incident light may be made to impinge upon the exact layer of fluid being examined. This calls for a focussing motion to the stage, but a similar motion to the body is also necessary, and a focussing adjustment is required for the stage as well as for the body.

In branches of research where a polarising prism is required to be used in combination with a wide-angle condenser more room is required between the stage and the mirror than is desirable for other purposes (see Fig. 108.)

This microscope combines all the requirements for these and other classes of research and forms a universal instrument for those who desire an instrument capable of doing exacting work of all descriptions.

The instrument stands on a heavy base, resting on three feet, which has two strong upright projections. These uprights have circular flanges along their inner surfaces which are accurately concentric with a point on the optic axis of the microscope. Between these uprights a solid segmental limb swings with channels which fit the V-shaped flanges of the uprights, so that as the microscope is changed from the vertical to the inclined or horizontal positions the centre of rotation is in the optic axis of the microscope and the centre of gravity of the microscope always lies near the centre of the base.

The segmental limb has a straight surface on the side away from the circular channels, provided with a parallel dovetailed slide along its entire length into which a rack in inserted. All the parts of the microscope slide along this dovetail. The upper slide focusses up and down by rack and pinion and carries the body, fine adjustment, and in the more complete instrument the rack-and-pinion draw-tubes, the high-power binocular or the petrological apparatus. A lower slide, which also focusses up and down by means of a rack and pinion, carries the stage, the substage, and the rest of the petrological apparatus. A third slide carries the mirror. The upper slide can be replaced by a Greenhough binocular body, and special slides can be supplied for the use of experimental apparatus. The general design of the instrument is thus a small optical bench swinging on a concentric fitting whose centre of rotation is in the optic axis.

A description of the instrument in its most complete form follows, but it may be supplied with as many or as few of the special adjustments as are required.

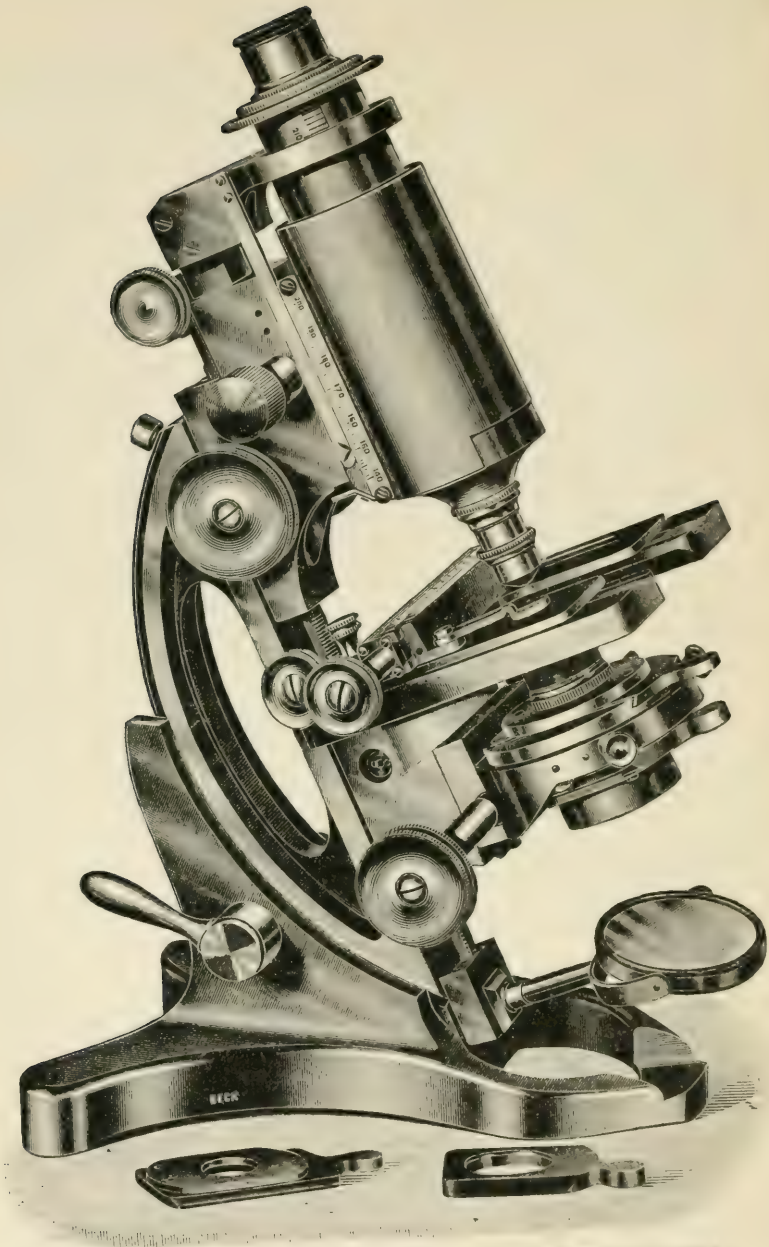


FIG. 107.—Radial Research Microscope. Complete model—square stage.

The Base has two feet behind and one in front. The back feet are 7½ inches apart and the distance from the front to the back feet is 7½ inches. It is provided with a clamp to fix the limb at any inclination from the vertical to the horizontal.

The Limb is 9¼ inches long on its flat edge. It is of massive construction and is open in the centre to form a convenient handle for lifting. Any of the slides can be moved along its entire length; this enables both the stage and the body to be placed low down; when the instrument is used in a vertical position (see Fig. 106) the microscope does not then stand higher than an ordinary small microscope; on the other hand, both the stage and the body can be placed high up on the limb (see Fig. 108), leaving a large space between the stage and the mirror for elaborate substage apparatus.

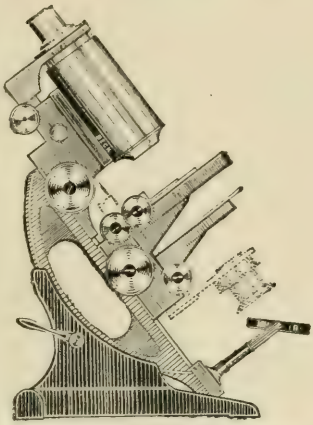


FIG. 108.—Radial Research Microscope, arranged to give great space for substage apparatus.

The Body Slide, moved on the limb by a rack and pinion, forms one of the coarse focussing adjustments. In the front portion of the body slide is a long fitting which carries the nosepiece, and which, actuated by a double lever, forms the double-speed fine adjustment. Two side milled heads operate the fine adjustment, the one on the right-hand side giving a motion of 4/10 millimetre for a complete turn, the one on the left a motion of 1/10 millimetre. The latter carries a drum graduated in 100 divisions, each division of which corresponds to 1/1,000 millimetre. The slow-motion slide carries the object-glass alone, and is thus not so liable to be affected by any jambing caused by the weight of a large body and eyepiece apparatus. In the case of the Dick apparatus of synchronised polarising prisms, it is almost impossible to make a perfect slow motion if the whole of this apparatus is moved by the fine adjustment. The 2 inch body tube is detachable.

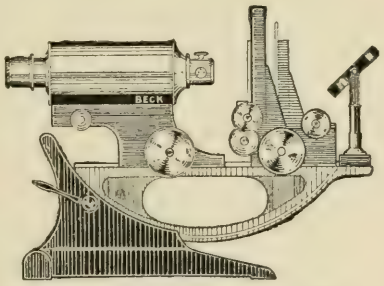


FIG. 109.—Radial Research Microscope, in horizontal position.

The Draw-tube Bar.—The body slide has a square hole down

its whole length in which a bar fits which can be extended about $2\frac{1}{2}$ inches by means of a rack and pinion at the upper end of this bar. A very strong bracket is fixed to the extending bar, which also carries a telescopic draw-tube. Any tube length, from 140 mm. to 250 mm., can be obtained.

The bar and the draw-tube can be entirely removed and can be replaced by a Beck Patent High-power Binocular body, (Fig. 113), which is actuated by the rack and pinion. This body is provided with rack-and-pinion adjustments to the draw-tubes, to enable the separation between the eyepieces to be varied to suit different interocular distances, and any change in tube length thus occasioned can be compensated by adjusting the whole body on the body slide while the object-glass remains fixed.

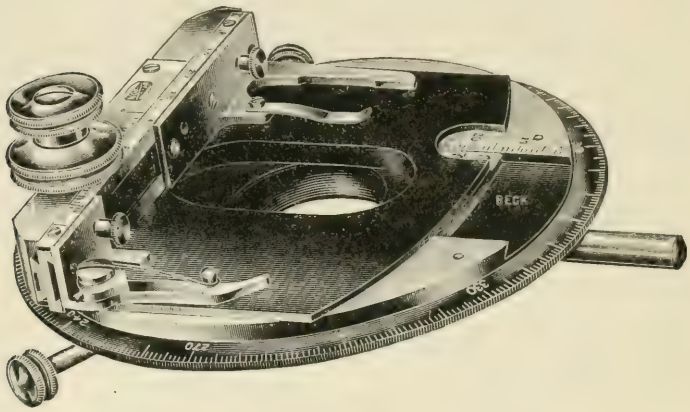


Fig. 110.

Experimental apparatus, such as a tandem microscope, spectroscopes, photometers, or a small camera, can be attached to the draw-tube bar without any fear of upsetting the action of the fine focussing adjustment.

The Stage Slide.—This is a massive bracket, the upper portion of which carries a circular rotating stage (Fig. 106) or a square stage with gap (Fig. 107). The lower portion of the stage slide carries a fitting along which the substage moves by means of a rack and pinion. No attempt has been made to provide a fine focussing adjustment to the stage in order that its great rigidity may be retained. A slide sufficiently delicate to form a sensitive fine adjustment would not bear the overhanging weight of a stage or the strain put upon it by manipulating the object.

The Stage.—Two forms of stages can be supplied. The one square, with a gap in the centre exactly similar to that supplied on the Massive microscope. The mechanical motions are

actuated by milled heads, projecting laterally on the right-hand side. The upper one moves the slide laterally and has 3 inches (75 mm.) travel, the lower one moves the slide vertically and has a motion of $1\frac{1}{4}$ inches (30 mm.). The latter motion is provided with a clamp screw by which it can be locked, so that there is no chance of the object moving when the microscope is in a horizontal position. Verniers reading to 1/10th mm. are provided to both motions for registering the position of specimens or for making measurements in connection with cross wires in the eyepiece. The whole mechanical portion of the stage with the upper plate can be removed, leaving a large square stage free for the examination of culture plates or other large objects; and as the optic axis is about 3 inches from the limb large specimens may be placed upon the stage. The gap in the front of this form of stage enables the substage apparatus to be more readily changed and gives ample room for the ultra microscope illuminating apparatus. The alternative stage is a circular rotating stage with centring screws (Fig. 110). This cannot be made with a gap, and therefore the substage must be racked down in order to change substage apparatus. It has mechanical motions with a lateral travel of $2\frac{1}{4}$ inches and a vertical travel of 1 inch. The graduated scales on the motions, although equally useful for measurement, are not so useful for registering the position of specimens, because they only give the correct readings when the centring screws are in one definite position, which is a troublesome adjustment to make each time a registration is required.

For petrological work a rotating stage is not required if synchronised polarising and analysing prisms are provided, and there are not many other purposes for which a circular stage is used, so that the square stage is the most generally useful. Both these stages are comparatively thin, and the mechanical motions are so devised that the movable plates do not come in contact with the front of the condenser or illuminators at any position of their travel.

The Substage.—This consists of a cylindrical fitting of the R. M. Standard diameter to receive apparatus. It is provided with a centring adjustment and rack-and-pinion focussing adjustment. On the upper surface of the substage fixed outside the standard cylindrical fitting, so as not to interfere with the insertion of standard apparatus, is a dovetailed slide (Fig. 111), into which fittings slide to which can be attached all kinds of illuminators on the principle devised by Mr. Akehurst. Illuminators so fitted can be made interchangeable, both as regards their focal distance and their centring, and a wide-angle condenser can be changed for a dark ground illuminator while the object is under observation. It is also much easier to centre a condenser accurately than a dark ground illuminator; and when this has been done the latter may be interchanged into the dovetail slide,

ensuring approximate centration immediately (see page 125). On the lower surface of the substage is a second dovetail fitting of an exactly similar form, which carries stops, diaphragm, polariser, etc.

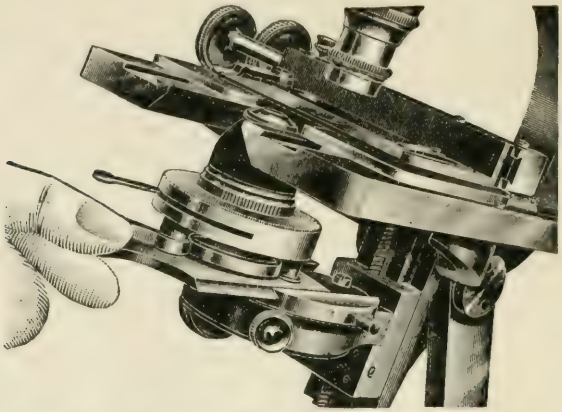


FIG. 111.—Akehurst Slides, for substage apparatus.

The Petrological Apparatus (Fig. 112).—The idea of rotating the polariser and the analyser together, instead of rotating the stage of the microscope and reading the angular rotation by a scale attached to the analyser, is due to Mr. Dick. It was carried out by a series of cogwheels and a connecting fitting at the side, which connection was rigid as regards rotation, but could telescope to allow of the focussing. It had two disadvantages. There was a tendency to loss of time in the cogwheels, and the strain on the slow motion in having to actuate a telescopic slide at a distance was liable to interfere with the perfection of the fine focussing adjustment. In this microscope the fine focussing adjustment, which only moves the nosepiece of the microscope, is free of the telescopic connection, and the synchronised rotation of the polariser and analyser is obtained without cogwheels by direct-acting links which turn the prisms on the principle of double connecting rods on an engine. It gives 180° of motion to the prisms, and either of the prisms can be rotated independently or can be rapidly swung out of the optic axis, returning to the same angular position.

The large 2 inch cover tube of the microscope body can be removed, leaving the rack-and-pinion draw-tube uncovered, and Bertrand lenses can be attached to the lower end of the draw-tube in slides by which they can be rapidly placed in or out of the optic axis of the microscope. An analyser or plate of tourmaline can also be inserted at the lower end of the draw-tube, or if desired a vertical illuminator can be attached in this position instead of

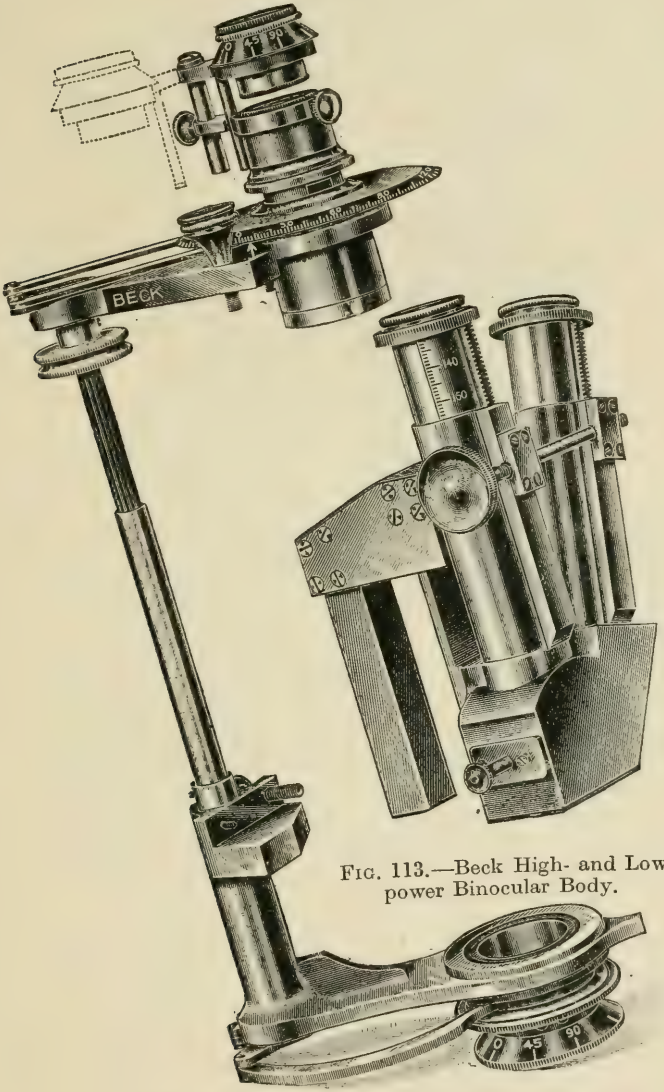


Fig. 113.—Beck High- and Low-power Binocular Body.

Fig. 112.—Petrological Apparatus.

on the nosepiece of the microscope. Under such circumstances even the motion of the fine adjustment has no influence on the alignment of the illumination, although there is seldom any necessity to consider such a refinement. A slot is provided in the eyepiece holder and the eyepiece for quartz wedges, quartz plates and other apparatus, and an eyepiece is provided with cross wires which rotate when the polariser and analyser are revolved in unison. A Becke Lens, with a micrometer in its focus, can be inserted in the analyser holder and used in combination with an eyepiece which has a Nelson analysing prism between the lenses.

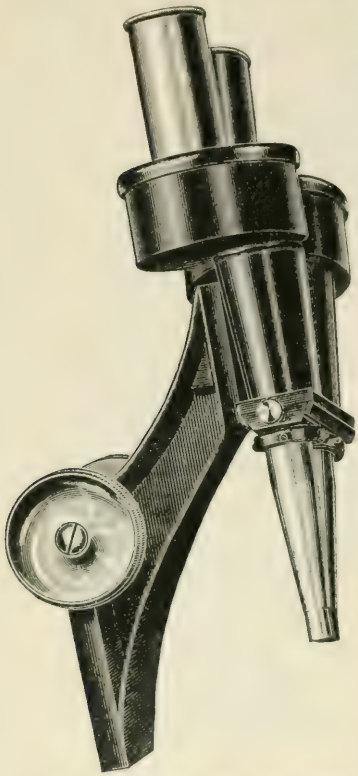


Fig. 114.—Greenough Binocular for Radial Research Microscope.

The High-Power Binocular (Fig. 113).—This binocular has been fully described in *The Microscope, A Simple Handbook*, pages 107–15. It fits to the Radial Research microscope in such a manner that whatever the interocular distance a large variation in tube length can be obtained.

The Greenough Binocular (Fig. 114).—This binocular body fits upon the limb of the microscope upon a separate slide, with rack-and-pinion focussing motion which takes the place of the body slide. It is only of use for low powers, while the high-power binocular is equally suitable for both high and low; but it has the feature that it gives without any adjustment, and with striking efficiency, an increased stereoscopic effect. Specimens stand out with astonishing solidity and depth, due to the combination of binocular vision with magnifying power. It consists of two separate microscopes, each looking at the object at the converging angle of the eyes when examining a near object. It erects the image so that it can be used for dissecting, and the full angle of aperture of each object-glass is used. In this respect it is an improvement on the old Wenham binocular, which cut the aperture of the object-glass into two semicircular halves (see Fig. 61*d*,

page 74). It, however, can only be made to give absolutely exact focus in the two eyes for the centre of the field of view. Objects to one side are at different distances from the two microscopes and cannot be in focus at the same time. It is not a serious disadvantage with low powers. The object-glasses are specially mounted, each pair being adjusted on a slide which fits into a dovetailed fitting at the nosepiece end of the body. Standard eyepieces can be used provided they are accurately paired. The following table gives the approximate magnifications obtainable with the different eyepieces and object-glasses and also their working distances;

Object-glass.	Magnifying with Eyepieces. 45 mm. ×6	25 mm. ×10	17 mm. ×15	Working Distance.
59 mm.	10	16	28	80 mm.
48 ,, ...	20	32	56	50 ,,
32 ,, ...	35	60	100	30 ,,
16 ,, ...	70	120	200	17 ,,

The large number of eyepieces and object-glasses sometimes offered with this type of instrument are not required, as with the above combinations all requirements are fully covered.

The Radial Research microscope has been described at some length because its numerous attachments and its great rigidity render it specially suitable for so many classes of research. It is supplied either complete as specified, or with only a plain 2-inch body with sliding draw-tube and with no substage, or with any or all of the additional parts.

Research Outfit

For those who desire to carry out research work under the best possible conditions, either with or without a microphotographic camera, great advantage is obtained if the whole apparatus is fixed on a bench or table with everything set up in the best position and in the most rigid manner possible.

There are many ways of carrying this into effect, but on the whole the author is of opinion that the best support is a strong teak table with the apparatus arranged as shown in Figs. 115 and 117.

The table in this arrangement has a top which measures 63 inches × 25 inches, and the figure only shows the right-hand end of the table, the left-hand portion being employed to carry the photomicrographic camera and the ultra microscope bench when required.

Fig. 115 shows the apparatus in the position for taking a photomicrograph, a portion only of the camera being included in the diagram.

The microscope and an optical bench, Fig. 116, carrying the

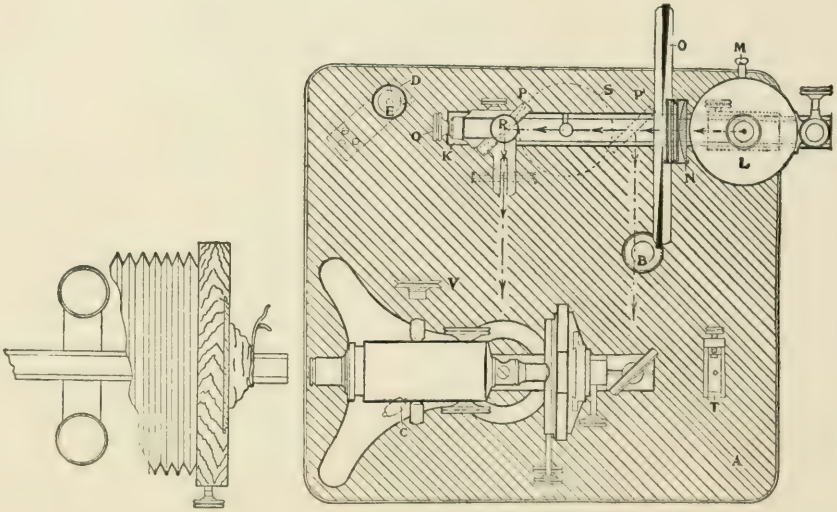


Fig. 115.—Radial Research Outfit with Optical Bench, Levelling Rotating Table, and Camera.

whole illuminating apparatus are fixed upon a supplementary platform or table (A), about 15 inches square. This table stands on four screws, by which the microscope may be levelled in either direction, and the whole board carrying the microscope and the illuminating apparatus revolves on a pivot, so that the microscope can be made to point towards the photomicrographic camera as shown in Fig. 115, or can be placed at an angle as shown in Fig. 117, or can be used for observation by observers sitting at the positions F, G, or H, so that the microscope can

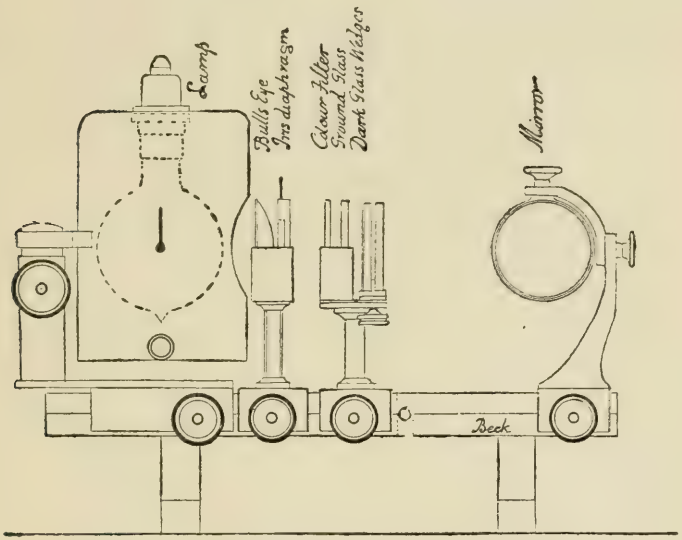


Fig. 116.—Optical Bench of Radial Research Outfit.

be used by different observers successively without upsetting any adjustments.

The illuminating apparatus is all carried on a strong steel bar fixed to the microscope board (see Fig. 116). At one end is a Pointolite electric lamp in a metal cover, which can be raised or lowered by means of a rack-and-pinion adjustment or can be moved laterally by the knob (M, Fig. 115). The lamp is carried on a sliding fitting with a clamp on the steel bar. Another sliding fitting carries a frame into which drop an iris diaphragm and a bull's eye condenser, and on a third sliding fitting is a pair of long neutral glass wedges which can be slid over each other, forming a perfect light moderator, and this fitting also carries two frames for colour screens. At the other end of the steel bar slides a frame which carries a mirror, one side of which is flat and the other concave. This mirror pivots in two directions

with comparatively stiff motions, one of which is on a horizontal axis parallel with the steel bar and is actuated by the milled head (Q. Fig. 115), the other of which is on a vertical axis which is actuated by the milled head (R, Fig. 115).

Fig. 115 shows this mirror so arranged as to direct the light into a vertical illuminator as used for opaque illumination with high powers. In order to change the illumination to transmitted light all that need be done is to slide the mirror along the steel bar (K) into the position shown by the dotted lines at P′, thus directing the light upon the mirror of the microscope. If the Radial microscope is to be used for observation in a vertical or inclined position, with the vertical illuminator, no change in the illumination is required, as it swings with the optic axis as a centre, and the position of the vertical illuminator, when set to the correct point, does not change by altering the inclination of the instrument. If, however, transmitted light is being used, as the microscope is turned from a horizontal into an inclined or vertical position, the mirror of the microscope changes its position, but the only alteration that is required in the illuminating apparatus is to incline the mirror (P) until it throws the light upon the microscope mirror. These are the only adjustments required for ordinary forms of illumination, but if an opaque object is to be illuminated by a beam of light thrown down upon the top of it between the object-glass and the object, then a small rotation of the mirror, by means of the milled head (R), must be made; and if the surface of the object be set upon the centre of rotation of the microscope, by racking the stage upwards on the limb, changing the inclination will not affect the illumination.

The advantage of this system is appreciated by those who, while generally carrying out work by visual observation, wish at any time to be able to take photographic records without having to rearrange the whole apparatus. In the case where an object is to be illuminated by a beam of light thrown upon it from above between the object-glass and the object, the concave mirror on the optical bench should be turned so as to concentrate the light to a focus on the object. The frame (N) which carries the condenser and the iris diaphragm can be removed from its holder, which slides on the steel bar, and inserted on a sliding fitting on the mirror holder. This is convenient for two purposes; firstly, when the instrument is used as shown in Fig. 115 for vertical illumination, an iris diaphragm and a ground glass placed in this position, as shown by dotted lines, enable critical illumination to be obtained, by setting the iris diaphragm at the same distance from the vertical illuminator as the eyepiece. In the other case it is useful to insert a bull's eye in this position for illuminating an object on the stage with a fine feather of light thrown between the object-glass and the object.

Fig. 117, which shows the microscope board swung round at an angle, illustrates a means of taking photographs without the microscope of large objects by means of a Microstigmar photographic lens with a focus of about 3 inches. The steel bar is provided with a hole and a clamp screw into which a circular table (S) of about 3 inches diameter drops, and can be clamped at any convenient height. Upon this an object can be placed; the microscope lamp is in a suitable position to illuminate it with a powerful beam of light, which can be modified by means of the mirror on the other side so as to prevent too great contrast or shadows. Objects from 1/2 inch to 1 inch in diameter can be

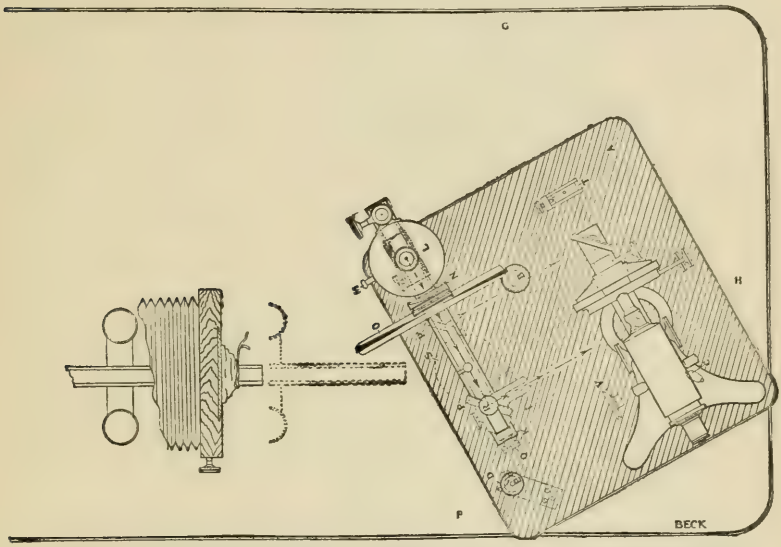


Fig. 117.—Radial Research Outfit, arranged for photography without the microscope.

photographed by this means from four to twelve times their natural size. The frame carrying the wedges (O) can be removed if it is in the way, and the photomicrographic camera, which is carried by four levelling screws in sockets fixed in the table, can be lifted out and dropped into a second series of sockets which brings the camera closer to the table which holds the object. The lamp (L) can be slid backwards on the steel bar to give rather more room for the camera.

For ultra microscopic work a special bench, as described on page 184, is required, with special illuminating appliances. This can be stood on the main table parallel to the photomicrographic camera; and when this is used the microscope board is swung round until the eyepiece faces the direction H. The front

levelling screw of the ultra microscopic apparatus is dropped into a socket (T) which is fixed on the microscope board. The microscope is set up so that the body is in a vertical position, and the gap in its stage allows the object-glass of the ultra microscope to go close to the object being illuminated.

This research outfit provides for every ordinary form of microscopic investigation, but if it is not required to take photographs or to use the ultra microscope the apparatus will still be of great service, especially as three observers can work together.

In this case a table about 24 × 36 inches is recommended instead of the long bench table. It will be found that there is no advantage in a long optical bench with large and costly condensers for any form of illumination except with extremely powerful arc lamps, as a small condenser placed close to a Pointolite lamp will collect as much light as a larger condenser, which must be placed farther away from it.

This outfit is equally suitable for any other kind of microscope than the one described, but in such cases an alteration in the illumination is necessary when a change is to be made in the inclination of the instrument. When this is so it is frequently useful to keep the instrument in a horizontal position and to make the observation by means of a right-angle prism (Fig. 118) fitting into the draw-tube of the microscope which can be removed when the photograph is to be taken.

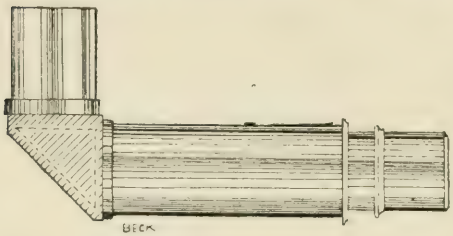


Fig. 118.—Right-angle Observing Prism.

For metallurgical work three forms of illumination are required:

1. With the thin glass or prism vertical illuminator, as shown in use in Fig. 115 or 106.

2. With an aplanatic ring illuminator over the object-glass, and the light thrown up upon it from the mirror below.

3. With a fine feather of light thrown between the object-glass and the object.

This outfit enables all these methods to be used in succession with very little change in the adjustments.

Two forms of photomicrographic cameras are supplied for this apparatus. Either a 1/4 plate camera with an extension of 30 inches, or a 1/2 plate with an extension of 36 inches. In both cases the cameras run on a strong steel bar which is carried on four levelling screws which are fixed on cross bars attached to the steel bar. Sockets are fixed into the table into which these cameras drop.

Fig. 119.—Greenough Binocular Microscope.

The 1/2 plate camera is provided with a bag attachment in the front to connect it to the microscope, or if preferred with a metal light-tight casing. This can be slid off and a Microstigmar photographic lens slid on in its place. Behind this board is an exposing flap for making the exposure. At the other end of the camera the back is reversible so that the plate can be put in a horizontal or vertical position, giving an upright or an oblong picture.

In the 1/4 plate camera the back is fixed and no exposure flap is provided, but an arrangement can be made to take a photographic lens in the front by screwing it on in place of the connection which joins the camera to the microscope.

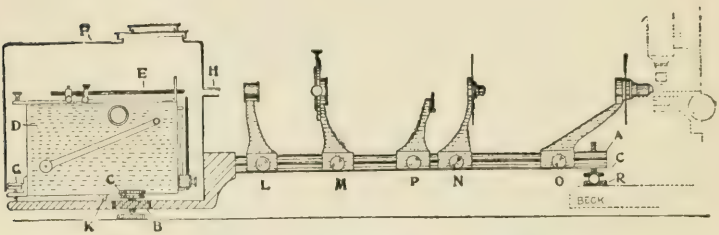


FIG. 120.—Ultra Microscope Illuminating Bench.

In Fig. 115 a pulley (V) is indicated on the microscope board opposite the slow-motion milled head. For photomicrographic work this is pushed on to the slow motion milled head, and by means of a series of cords and weights connected to a drum at the left-hand end of the photomicrographic camera, the microscope can be focussed on the ground glass even when the camera is extended to its longest position.

Various devices have been used for making this connection, but a good deal of experimental work has shown that with a light cord and weights there is less liability to backlash than with any system of more rigid connection. In addition to which it is extremely simple to detach the cord from the pulley when the microscope is to be used for observation.

The Greenough Binocular is supplied as a separate microscope on a stand with joint, as illustrated in Fig. 119. The upper portion, comprising the body, the limb, and the focussing adjustment, is detachable and can be fixed to a horse-shoe plate for standing upon a table or can be fixed down to a bench if it is required for dissecting. This form of binocular microscope is also fitted to the "crescent" dissecting microscope and makes a very firm and convenient model in this form (page 192).

Ultramicroscopic Outfit.—An outfit for this purpose (Fig. 120) is made mounted complete on an optical bench suitable for use with the Radial Research microscope or similar instruments. It consists of a strong steel bar (A) 24 inches long, carried upon a cross bar (B) which is supported on two levelling screws and upon a third levelling screw at the front end of the bench. Projecting over one end of the bar is fixed an automatic arc lamp (D), of 5 to 8 amperes, which has the positive carbon (E) horizontal and the negative carbon vertical. The crater of the arc is thus directly facing the optic axis of the bench. The arc lamp is enclosed in a lamp house (F) with side doors and with a small tubular aperture (H) in the front to allow the light to emerge. The lamp has a small raising and lowering motion (G), and a small lateral movement obtained by swinging on the pivot (K). A series of fittings slide along

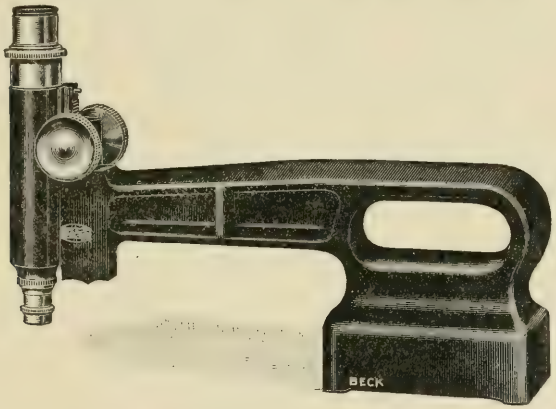


Fig. 121.—Process Microscope.

the steel bar; the first one (L) carries an achromatic lens system for focussing an image of the crater of the arc upon the next fitting (M), which carries an adjustable slit which has a rotating movement and side cheeks for limiting the length of the slit. A fitting (N) carries a 32 mm. achromatic lens system by which an image of the slit is projected along the optic axis five times smaller than the slit. At a distance of about 280 mm. from this lens system a special microscope object-glass (25 mm. focus, N. A. ·24) is carried upon another fitting (O) on the bench. This object-glass has a working distance of 9 mm. and allows of the use of the highest-power lenses without touching the mount of the observing lens. Between the slit and the projecting lens an adjustable chisel edge is carried on another fitting (P), by which the beam of light can be restricted in height.

The adjustments having been made on the optical bench, to ensure proper centring, the whole bench can be adjusted

vertically by the three levelling screws. The levelling screws stand on metal plates; the front one (R) is provided with a screw adjustment, so that the whole bench can be moved laterally.

The Process Microscope (Fig. 121).—This microscope owes its name to the fact that it was first designed for the examination of photomechanical plates during and after the operation of etching. Such "Process" plates are immersed in the etching fluid in trays, and the microscope overhangs its base to such an extent that the whole area of a 15 × 12 tray can be examined. It has also been used for examining live objects in shallow aquaria, for the examination of engravings, diagrams, or other large flat objects, and is a useful form of instrument for many industrial purposes.

It will take all standard eyepieces and object-glasses. It has a rack-and-pinion focussing adjustment and an extending draw-tube, and has a space of about 3 inches between the supporting arm and the table.

If the eyepiece is fitted with a micrometer it can be used for measuring Brinell tests or small parts. It can be supplied with such a magnifying power that the divisions of the eyepiece scale represent decimal parts of either an inch or a millimetre.

FIG. 122.—Goniometer Eyepiece.

A useful eyepiece (Fig. 122) can be supplied to this or other microscopes for the measurement of angles. This consists of a revolving eyepiece with cross wires, combined with a scale of degrees on the outside, by means of which the rotation required to place a line against the two sides of an angular object can be observed.

The Museum Microscope (Fig. 123).—This form of instrument, although it can be used for many purposes, is particularly suitable for examining objects which cannot be placed upon a glass slip on the stage of an ordinary microscope.

A microscope body with a rack-and-pinion focussing adjustment and a draw-tube is fitted on an arm which slides up and down and is clamped on a bar about 10 inches high. This bar is fixed at a corner of a strong wooden stand upon which an object to be examined may be placed.

The microscope is provided with two additional rack-and-pinion motions, one to move it laterally and the other to move it vertically, so that when it is clamped at a convenient position on the supporting bar it may be racked up and down about 2 inches either way, or may be racked 2 inches to the right or to the left. These movements are both at right angles to the axis of the microscope. The whole microscope, together with its adjusting slides, may be turned on a horizontal axis and clamped in any position, so that the axis is either horizontal, oblique, or vertical. By

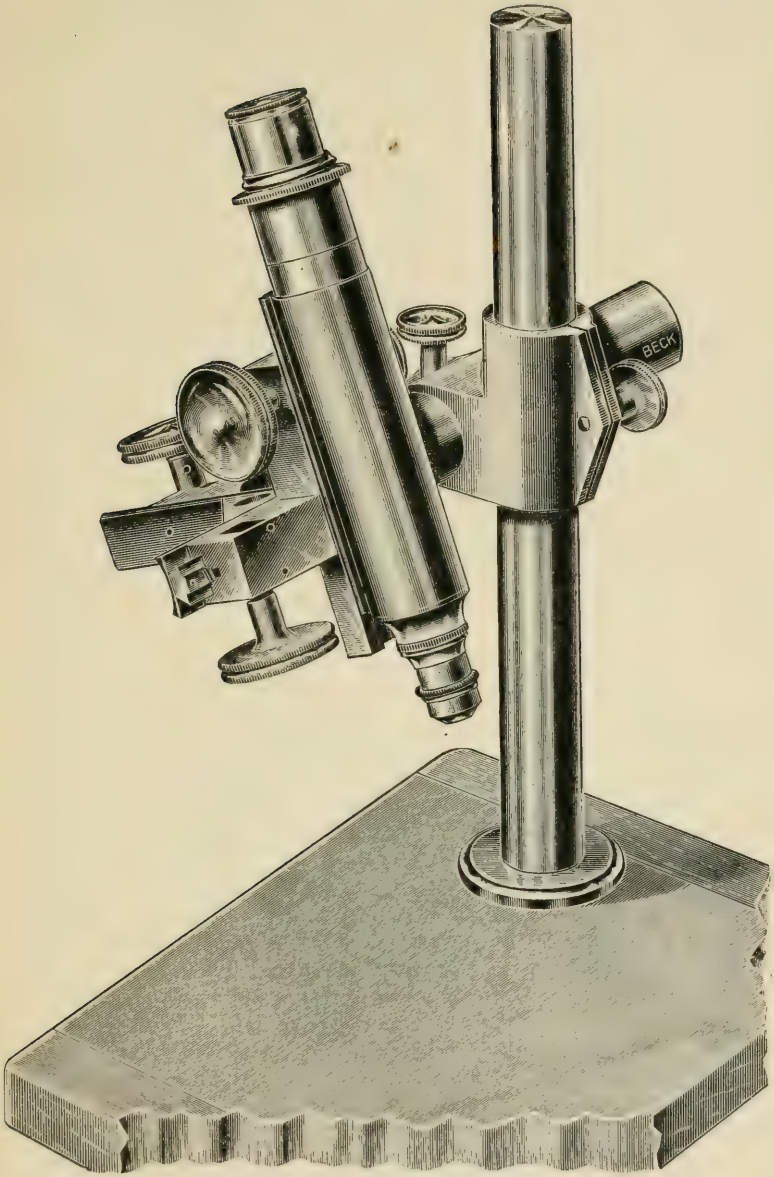


Fig. 123.—Museum Microscope.

this means an object of any shape may be examined and the axis of the microscope can be set at right angles to the portion of the surface being examined. It is particularly intended for such objects as minerals, porcelain vases, logs of wood, skin, fur, plaster or enamel ware, or any of the numerous objects of irregular shape and size which go to form the contents of a museum.

If the axis of the microscope is set in a vertical position, objects in a tank of fluid may be observed or diagrams or engravings may be studied. If it is set in a horizontal direction it may be used to examine the contents of an aquarium.

If the rack-and-pinion motions are provided with scales and verniers it can be used as a micrometer microscope on objects in either a vertical, horizontal, or inclined position.

It can be provided with a Greenough binocular body if desired, and can also be provided with a small removable stage and mirror to enable it to be used as an ordinary microscope. With a special long-focus low-power optical system it is useful for examining objects in show cases. For this purpose the whole microscope is swung round on the vertical bar, so that it overhangs the stand on one side and the stand can be stood upon the glass of a show case. It takes any standard object-glasses and eyepieces.

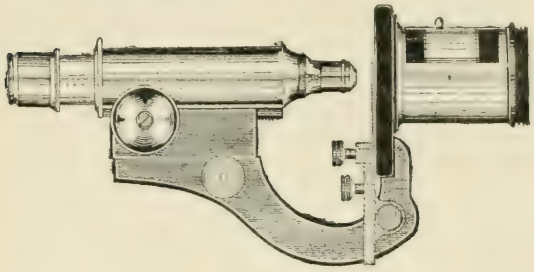


Fig. 124.

Projection Microscope (Fig. 124).—An attachment is made to fit on to an optical lantern for microscopic projection which consists of the stage and body portion of an ordinary microscope combined with a substage condenser constructed to work in combination with the lantern condenser and a water cooling trough. Such an apparatus is useful for low powers, but is of very little service for high powers on account of the difficulty of obtaining a sufficiently powerful light. To use a 1/6 inch object-glass on a comparatively small screen requires a 20 ampere arc lamp, and the heat which is condensed upon the object is difficult to absorb. Microprojection has, therefore, never been largely employed. Photomicrographs thrown upon the screen by an ordinary lantern are greatly to be preferred. For experimental work the Research microscope on an optical bench which also carries the lamp and cooling troughs, if screened with curtains, forms as perfect a projecting microscope as can be made. It is best to have a

bench specially arranged for this purpose with a very high-power arc lamp and a very large cooling trough.

The Tandem Microscope.—In the early days of the microscope the use of two microscopes, one behind the other, one of which magnified the image produced by the other, was suggested and actually used. There is no advantage in such a system. The use of a complete microscope as an exceptionally powerful eyepiece to magnify the image formed by both a microscope and a telescope object-glass has been largely advertised. Consideration of the problem of microscope resolution shows that extra magnifying power at the eyepiece is of little value unless accompanied by extra aperture in the object-glass. The full aperture of any object-glass can be taken full advantage of by ordinary eyepieces, which are of a much less costly and elaborate design.

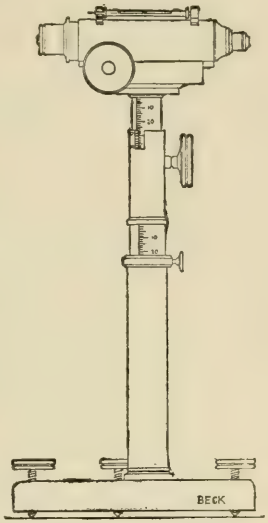


FIG. 125.—Horizontal Reading Microscope.

Horizontal Reading Microscope (Fig. 125).—A simpler form of microscope than the Museum microscope is made for physics research and for reading heights, etc., which may also be used for the examination of living specimens in an aquarium. It consists of a microscope with horizontal tube which carries the object-glass and eyepiece and which is provided with a rack-and-pinion focussing adjustment. The microscope is carried on a strong stand with a rack-and-pinion and a sliding adjustment for raising and lowering. The microscope tube can be placed at any level above the table between 13 and 21 inches. It may be used in conjunction with a stand to raise the aquarium to a convenient height. The instrument is carried on three levelling screws and the tube is provided

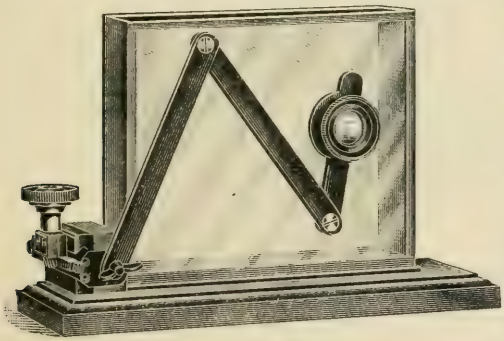


FIG. 126.—Tank Microscope.

with a spirit level. It can be turned into a reading telescope by replacing the microscope object-glass by a telescope object-glass.

An achromatic magnifier, with complete adjustment fixed to a stand upon which a small aquarium may be placed, is a useful appliance for studying aquatic objects or materials in solution. It is known as a tank microscope (Fig. 126). The most suitable aplanatic lens magnifies about 5 or 8 diameters and is provided with a rack-and-pinion focussing adjustment. By means of jointed arms it can be travelled over all parts of the tank or aquarium.

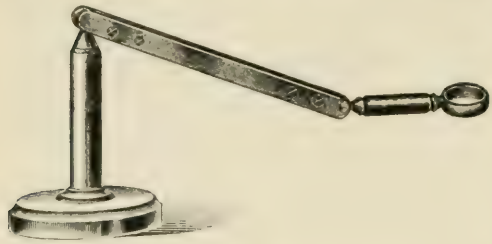


Fig. 127.

Dissecting Microscopes.—The simplest forms of dissecting microscopes consist of well-corrected aplanatic lenses mounted on adjustable stands. Fig. 127 shows a stand with a series of arms with ball-and-socket joints for adjusting the position of a ring holder into which lenses of different magnifying powers can be fitted. Fig. 128 shows a similar apparatus on a heavier stand with a rack-and-pinion focussing adjustment to raise and lower the adjustable arms and the lens.

Fig. 128.

A small non-inverting compound microscope, known as a Brucke lens, which gives a magnifying power of from 30 to 50, can be used in these stands (see page 29), but it has such a small field of view that it is only useful for the occasional examination of a small portion of the object under a high magnifying power. A small compound microscope of about the same power which gives an inverted image and has a large field is more satisfactory in every way except as regards the inversion of the image. This can be overcome by a prismatic eyepiece, which, however, is too heavy to be used on these simple stands but works very well on the more complete dissecting microscope described below.

The Crescent Dissecting Microscope (Figs. 129–132)

(Monocular [Single or Compound] or Binocular)

The ordinary dissecting microscope has followed the lines of a compound microscope stand to which side hand rests have been added. Such a construction is unsuitable for dissecting, as the weight of the hands upon the hand rests has a tendency to upset the instrument.

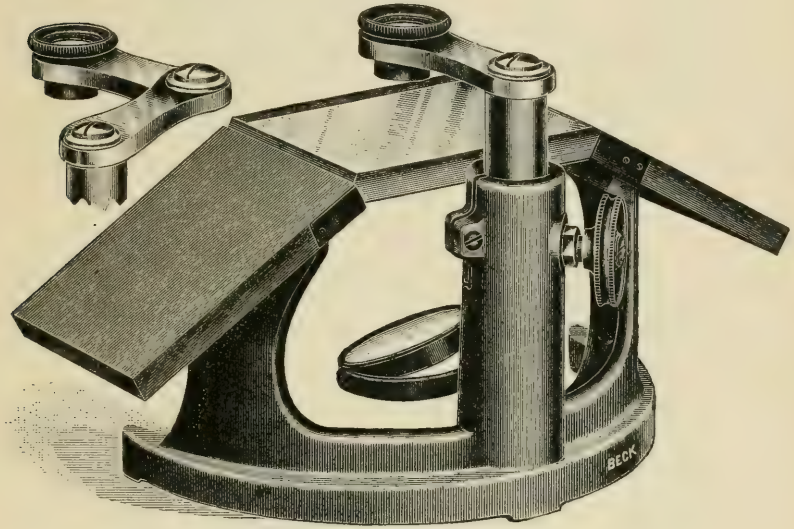


Fig. 129.—The Crescent Dissecting Microscope.

This very rigid form of dissecting microscope is designed for the purpose for which it is to be used, and the supports are under the hand rests and are an integral portion of the base, the whole instrument being absolutely steady and firm. The hand rests are of hard wood fixed to the base and the stage is a thick plate of glass. The base is a heavy casting resting on three slight projecting feet, with two uprights to support the hand rests and stage, and a pillar at the back within which fits a solid rod to which is attached at the top a swinging arm for the lenses. This rod is focussed up and down by a rack and pinion actuated by a milled head, which is placed at a convenient angle for the hand. It has a motion of over 3 inches, so that very thick specimens can be examined. Below the stage, and swinging in gimbals, is a mirror, silvered on one side and opal-white glass on the other.

The instrument is so solid that it can be used as a compound microscope, either of the erecting or inverting type, by attaching a tube either with or without erecting prisms on which any of

FIG. 131.—Erecting Compound Microscope Tube for Crescent Dissecting Microscope.

FIG. 130.—Non-Erecting Compound Microscope Tube for Crescent Dissecting Microscope.

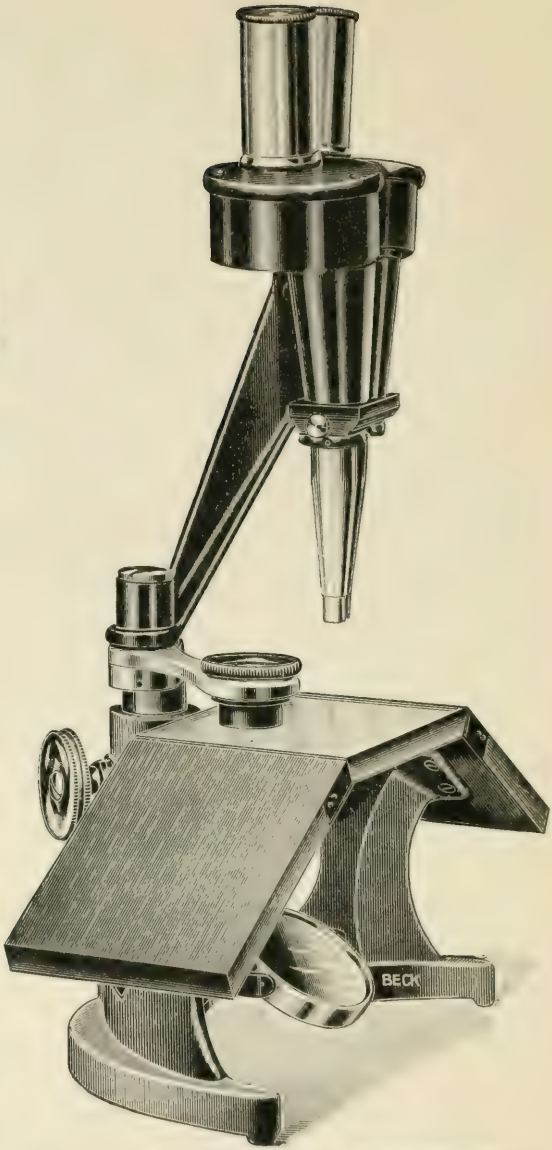


FIG. 132.—Crescent Dissecting Microscope, with Greenough Binocular.

the standard object-glasses or eyepieces can be used (Figs. 130, 131).

For work where the highest powers are not required, it forms a very satisfactory compound microscope at a low price.

The instrument is illustrated with a single swinging arm for holding the lenses or the microscope tube. It is supplied also with a double arm if it is desired to move the microscope over the specimen rather than to move the specimen under the microscope.

The instrument is also supplied with the Greenough Binocular body (Fig. 132), which is fitted on a second swinging arm, so that it may be swung to one side while an ordinary lens is used for searching. This form of stand with a Greenough Binocular body has many advantages over the binocular body screwed

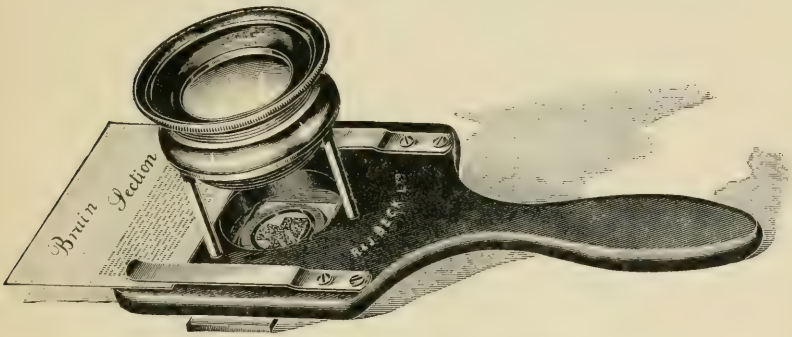


FIG. 133.—Demonstration Microscope.

down to a bench. It is easier to dissect with, it is a more comfortable height, and transparent objects can be worked with.

Figs. 130 and 131 show the two forms of compound monocular microscope bodies applicable to this instrument which take standard eyepieces and object-glasses.

Fig. 130 gives an inverted image, Fig. 131 gives an erect image.

Demonstration Microscope (Fig. 133).—This instrument is a low-power microscope consisting of a hand lens fixed to a stage with a handle. It can be held in the hand so that a specimen can be set up, focussed, and passed round a class.

Sand and Dust Microscope (Fig. 134).—This instrument is designed for use in mines for the rapid examination of dust particles. It consists of a microscope body with a magnifying power of about 50 diameters, sliding in a cloth-lined projection of a wooden block. A second projection of the wooden block carries two stage springs and forms a stage to carry a 3 × 1 inch glass slip on which the dust to be examined is placed, preferably under a thin cover-glass. Below the stage and supported by a

thick projection of the wooden block is a small electric torch, and between the torch and the stage is a lens system with its central portion obscured so that it throws an oblique ring of light upon the object and illuminates it against a dark ground. The composition of many kinds of sand and dust can be rapidly determined by this portable instrument.

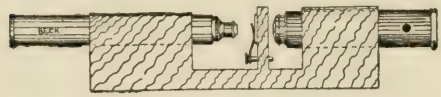


Fig. 134.—Sand and Dust Microscope.

Field Microscope for the Mining Engineer (Fig. 135).—This instrument consists of a tube (A) which carries an eyepiece (I) and a 2/3 inch object-glass (O) giving a magnifying power of 60 diameters. Above the object-glass is a thin glass transparent reflector (B) by which light coming through the aperture (C) can be reflected through the object-glass upon the specimen (D) being examined. The tube carrying the lenses screws up and down in the flanged fitting (E) by either revolving the tube or by holding this stationary and revolving the fitting (E). The specimen to be examined is mounted in a loose metal box (F) with wax (G) in the following manner. A lump of S.I.R.A. wax (G), which has been rendered pliable by kneading with the fingers, is placed in the box, being of such a size that it projects above the upper surface of the box. The specimen is then placed on the top of the wax and the box turned upside down and pressed upon a flat surface. The surface of the specimen is thus rendered flush with the upper edge of the box (F) and the microscope is stood upon this edge to examine it. By pulling the eyepiece in and out of the upper end of the tube a delicate focussing adjustment can be obtained.

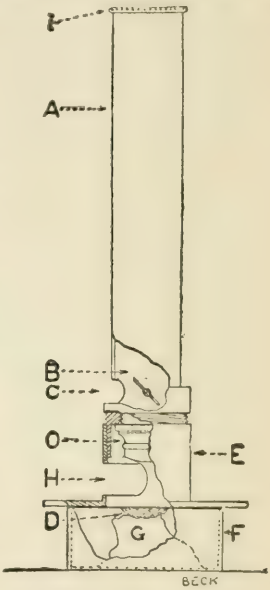


Fig. 135.—Field Microscope.

A gap (H) is cut out of the flanged fitting (E), so that illumination may be obtained upon the object direct instead of by means of the reflector (B) if desired, and reagents can be applied to the specimen while under observation.

The instrument takes standard object-glasses and eyepieces so that various powers can be obtained.

To prepare specimens of ore and rocks for examination they

generally require to be ground and polished to a flat surface, and for this a set of apparatus with carborundum, emery, rouge, and diamantine powders, with grinding and polishing plates, etc., is convenient.

The Inverted Microscope.—For the examination of metals and for certain chemical experiments a special form of microscope is made in which the stage is at the top and the specimen to be examined is placed face downwards upon it. The object-glass is underneath the stage, and below this is a right-angle prism which deflects the light into a horizontal tube which carries the eyepiece. This form of microscope has certain advantages for its own particular work. It is provided with two horizontal observing tubes, either of which can be used by revolving the prism which is below the object-glass. They can be arranged so that either two observers can use them in succession or one may be used for photography and the other for observing. A third tube is supplied through which, by means of a suitable reflector, the object is illuminated by a beam of light thrown through the object-glass upon the object.

The Beck Inverted Microscope consists of a strong tripod which carries a cylindrical box about 8 inches above the table. Within this upright cylinder are carried the central revolving prism and the reflectors. Two fixed body tubes and an illuminating tube project from it at three right angles. The fine adjustment moves the object-glass alone. The coarse adjustment moves the entire stage up and down, which is so strong that heavy specimens can be placed upon it. A mechanical stage can be attached to the plain stage when required. The illuminating reflectors are provided with adjustments of much greater delicacy than are supplied with ordinary vertical illuminators, whereby they can be moved laterally in a dovetailed slide and can be inclined in two azimuths, and their positions can be registered.

For the use of the Beck Aplanatic ring illuminator a mirror can be provided above the stage, and a large range of motion is supplied to the stage to allow of the use of a Microstigmar photographic lens for the photography of large objects. The design of this microscope at the time of going to press was not completed in all its details and an illustration could not be inserted, but full particulars can be obtained from the makers.

CHAPTER IX

POLARISED LIGHT AS APPLIED TO THE MICROSCOPE

Plane polarised light—Crystalline structure produces polarisation—Polarising prism—Tourmaline—Analysing prism—Rotation of plane of polarisation—Retardation and interference—Retardation without interference causes circular or elliptical polarisation—Interference patterns caused by convergent light—Polarisation by reflection—The Petrological Microscope—Retardation plates—Wedges—Babinet compensator—Bertrand quartz plate—Stauroscopic plate—Savant plate—Double-image prism—Dichroiscope—Goniometer eyepieces—Stage goniometers—Various goniometers—Refractometers—Spectroscope eyepiece—Shand micrometer.

POLARISED light plays such an important part in some branches of microscopical study, that although it is beyond the scope of this book to enter deeply into the theory, an attempt will be made to give a general idea of the elements of the subject.

In the chapter on Resolution it was explained that light was assumed to be due to a wave motion, to a vibration of particles of ether, each particle vibrating up and down like a cork on the surface of a rough sea. The particles themselves do not travel along in the direction of the wave motion, but merely move up and down at right angles to the movement of the wave. The light wave travels from A to B, Fig. 136, but any particular particle moves up and down as from C to D. The particle is at rest at the central position (X) until it is acted upon by a light wave, but as soon as it is caused to vibrate it oscillates between C and D, and when the light wave ceases resumes its original position; it is indeed supposed to be acted upon all the time by a force that tends to pull it back to its original position. Suppose a section of the wave is made at right angles to the direction of propagation (Fig. 137), the particle will be oscillating from C to D; but what governs the direction in which it oscillates? Why should it oscillate between C and D? Ether is supposed to be a perfectly homogeneous medium, and why should it not oscillate along the line E F, or G H, or in any other direction in the plane of the paper? It is necessary to suppose that it oscillates in all these directions in order to explain polarised light. It is difficult to imagine a

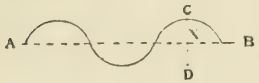


FIG. 136.

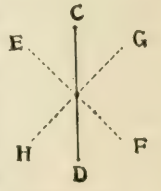


FIG. 137.

single particle oscillating in more than one direction at the same time, but it is not difficult to imagine it moving first along the line C D, then along the line E F, and after that along the line G H, so that it oscillates in all directions at right angles to the direction of the wave in rapid succession, and we may consider that, as it is moving in all these directions within such a short period of time, it produces effects as if it were moving in all these directions at once. The complete explanation of the nature of light is probably not so simple as the motion of a single particle in a homogeneous and perfectly elastic medium called ether, but the wave theory hypothesis of light has been proved to be accurate as regards most of the observed phenomena, and is perhaps as correct as the statement that the earth is round, when we know that strictly speaking it is not a perfect sphere. The conception that light causes any particular particle of ether to vibrate at right angles to the propagation of the light, and to oscillate in any and every direction at right angles to the line of propagation, is sufficiently correct to form the basis of the explanation of polarised light.

Suppose such a ray of light enters a crystal. A crystal is known to have its molecular structure arranged in a peculiar manner. Its particles are regularly spaced and are closer together in one direction than another. A regiment of soldiers standing in rows 6 feet behind each other and each man standing 6 feet from his neighbour in each row would be a perfectly symmetrical arrangement, and would be similar to the particles of a homogeneous medium, such as glass; but suppose that without altering the distance between the rows, the men in each row were to close up till they were only 1 foot apart, the interstices between the men would be 6 feet in one direction and 1 foot in the other. This arrangement is analogous to the particles in a crystal.

There are many forms in which a regiment of men can be arranged, and similarly many varieties of crystalline structure, but they all have the property that the density in one direction is different to the destiny in the other.

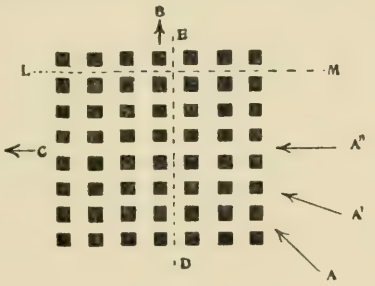


Fig. 138.

Suppose we represent the soldiers by square posts driven into the ground (Fig. 138), and suppose that a wind blows through such a series of posts. No matter from what direction it enters it will be directed along the channels L M and E D between the posts; it can only continue its motion in two directions; it must ultimately pass

through one or other of the rows. If it enters in the direction A it will emerge in the direction B and C. If it enters in any other direction it can only emerge in the direction B or C. More will emerge in one direction than in the other, according to the angles at which it enters. This latter point is a matter of importance in view of phenomena described later. Suppose the direction A is at 45° to both the channels E D and L M, then an equal amount of light will pass down each channel. One may be retarded by the narrowness of the channel, but the intensity on emerging from the crystal will be equal; but if the direction at which the light vibration enters the crystal at A′ is more nearly parallel to the channel L M, then a greater proportion will pass down the channel L M until, if the light vibration is exactly parallel to the channel L M, the whole of the light will be vibrating in this direction and none will be vibrating in the direction of the channel E D.

That is what happens when a ray of light passes through a crystal. The ether particles are oscillating in all directions at right angles to the line of propagation when they enter, but they will only be vibrating in two directions when they leave; these two directions are always at right angles to each other; but it will also have produced another result. Light, when it enters any transparent material, is retarded in speed, but in such crystals whose particles are closer together in one direction than in the other, the two sets of rays which emerge from the crystal will be retarded to a different extent.

The bending or refraction of light is due to this retardation which occurs when it enters a dense medium (see page 37), and therefore the two kinds of rays, one of which is retarded more than the other, are refracted to a different extent and the phenomenon of double refraction is met with.

If one ray of light enters a crystal of this description it will be converted into two rays, one of which is bent or refracted more than the other, and these two rays are both said to be polarised; that is to say, all the vibrations in one ray are moving in one single direction, all the vibrations in the other ray are moving in another single direction, and the two directions of vibration are at right angles to each other. Suppose in Fig. 139 a ray of light at right angles to the paper enters a crystal at A with the particles vibrating in all directions, as indicated by the dotted lines, it will emerge as two rays B and C, and the particles in these rays will all be vibrating in one direction in B and in another direction in C, and these two directions will be at right angles to each other.

FIG. 139.

What is known as a polarising prism, or a polariser, is made of

a crystal of Iceland spar, which possesses the quality of double refraction to a considerable extent.

It is cut to the shape shown in Fig. 140, and is slit in half along the line D F and cemented together with Canada balsam. A ray of light (A) is divided into two rays (B) and (C) and refracted differently; the ray B is bent considerably to one side, and, due to the difference in refractive index between the spar and Canada balsam cement, this ray, which meets the surface D F at a much greater angle than the ray C, is totally reflected at the surface and does not pass through the prism, and the whole of the light which emerges from the prism is similar to the ray C and is vibrating in one direction, or is said to be polarised.

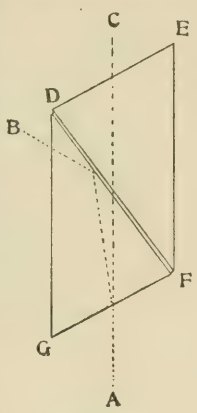


Fig. 140.

There are several other shapes and varieties of polarising prisms, but the one figured is the usual form, and is called a Nicol prism.

Certain forms of crystals entirely quench or absorb one of the two rays and allow only one to pass through, but such crystals are not generally sufficiently transparent to be useful. Tourmaline, however, although coloured, is partially transparent in some of its forms. A dark brown variety is used for some purposes, but is so strongly coloured as to be of little service for microscopic observation. There is, however, a light green variety which if cut in sufficiently thick plates (about 4 mm.) forms a most excellent polariser for all purposes except where it is necessary to distinguish delicate shades of colour, and is far more satisfactory than a prism if polarised light is being used for the purpose of cutting off glare or for increasing resolution, as described on page 130.

A polarising apparatus is, however, not complete with only one prism. The light which is passed through it will be polarised, but a similar prism used above the polarising prism, and called an analysing prism, or analyser, is necessary to complete the apparatus. When using these two prisms on the microscope the polariser is fitted in the substage below the object, and the analyser is fitted is some portion of the body of the microscope, so that one prism is on each side of the object being observed. There are then two similar prisms, each of which has the property of only allowing the light to pass through which is vibrating in one plane. If these two prisms are placed so that they are parallel as regards the direction of vibration, then the light that passes through the polariser will also pass through the analyser; but if the upper prism is rotated 90°, then the direction of vibration of the light which enters it will be at 90° to the direction which the analyser

allows light to pass through and it will not emerge, and the polarised ray which enters the prism will be extinguished; and upon looking through the microscope, with the two prisms so arranged, the field will appear to be dark. No prisms entirely polarise all the light; if the light is sufficiently intense, a small amount will pass through, but with light of moderate intensity the field will appear black.

If the analyser be turned to an intermediate position, a portion of the light from the polariser will pass through the analyser; and thus, as the analyser is revolved, the field will change from a totally dark to an entirely bright field.

A polarising apparatus, consisting of a polariser below the stage of the microscope and an analyser above the stage, is used for the examination of objects which are said to polarise light. Such objects include all crystalline materials, the various components of igneous rocks, and most chemical substances in their crystalline state. It includes a number of semi-crystalline materials, such as horn, wax, starch, fibres, and numerous organic compounds. The study of the constituents of rocks with polarising apparatus has been developed to a high state of efficiency by the means of the petrological microscope, and the principles by which the crystalline contents of a rock are identified are here briefly indicated.

Suppose that a plate of a tourmaline crystal be placed on the stage of the microscope. Viewed by ordinarily unpolarised light it will appear coloured, but otherwise transparent. Its colour may be either brown, green, or pink, according to its variety. Different specimens will be of different depths of colour, but there is nothing to distinguish it from coloured glass or several other materials. But suppose a polarising prism without the analyser be placed below the stage, the tourmaline is now being illuminated by a beam of polarised light; that is to say, by light vibrating in one direction. Suppose that A B C D, Fig. 141, represents a thin plate of tourmaline and that the light that is thrown upon it by a polariser is all vibrating in a direction parallel to E F, the effect of the crystal upon this light E F is to turn it into two beams of light, G H and K J, vibrating at right angles to each other; and moreover, this particular kind of crystal, if sufficiently thick, has the power of absorbing or quenching one set of these rays, G H, so that the only light that now passes through the crystal is vibrating in the direction J K. The practical result of this has been to rotate the plane of polarisation of the beam of polarised light from the direction E F to the direction K J. If before inserting the plate of tourmaline the analyser had been put upon the microscope and

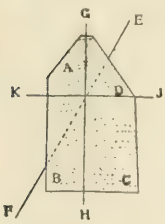


Fig. 141.

revolved until it was at 90° to the plane of the polarising prism, so that the light was totally extinguished, the insertion of the plate of tourmaline would have allowed the light to pass through the analyser, and total extinction of light would only have been regained by rotating the analyser till its principal axis was at right angles to K J instead of E F.

To return to the examination of the tourmaline crystal with the polariser alone, as Fig. 142. If instead of using the analyser

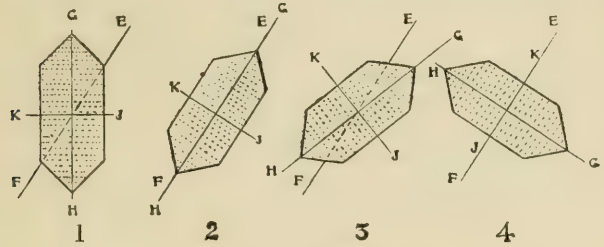


FIG. 142.

the tourmaline crystal is revolved while the polariser remains stationary the following appearances are observed :

When the crystal is placed as at 1, so that the axes are at an equal angle 45° to the incident beam, E F, the light E F has been divided into two beams, G H and K J, and each beam will have equal intensity ; one of these has, however, been quenched, and therefore the light has been diminished by one-half. As it is turned slightly in the direction of the hands of a clock, more light goes into the direction G H and less into the direction K J (see page 198), until, when the tourmaline has been rotated to a position 2, where G H is parallel to the incident light, the whole of the light which enters the crystal is along the direction G H, and all this is absorbed or quenched, so that the crystal appears to be black. Further revolution sends more light into the direction K J and the crystal begins to transmit more and more light, until when it reaches the position 4, where J K is parallel to E F, the whole of the light is transmitted and the full brilliancy is obtained.

Rotating the tourmaline gives, therefore, total opacity in one position, complete transparency at 90° to this position, total opacity at 180°, and complete transparency at 270°, reaching total opacity again at 360°.

If the plate of tourmaline is less than a certain thickness the second ray is not entirely absorbed, and thus, although a darkening is met with, it is never entirely opaque. There are a number of minerals which have this quality of absorbing one set of rays to a considerable extent, though few to so large a degree as tourmaline. Hornblende, andalusite, and biotite, for instance,

all show very marked darkening in their colour as they are rotated.

The importance of a rotating stage almost universally supplied on a petrological microscope is apparent, the more so because, although all these minerals convert a polarised ray of light into two rays which vibrate at right angles to one another, the direction of these resultant vibrations with relation to the characteristic edges of the crystals is different in different materials, and a further means of identification is thus provided.

The question then arises as to what happens when a crystal divides a beam of polarised light into two beams vibrating at right angles to each other, neither of which is partially or totally absorbed. Both rays emerge, and if such a mineral is placed over a polarising prism no result is noticeable. It requires an analyser to discover the result.

Let us suppose that a beam of polarised light with vibrations in the direction A B, Fig. 143, passes through a crystal, and that the light upon emergence is in the directions F G and H J. Now if a rotating analyser be placed above the specimen with its plane of vibration parallel to H J, light from the beam H J will completely pass through and the field will appear bright. When it is rotated so that it is at 45° to H J and 45° to F G, half the light from H J and half the light from F G will pass through; and when it reaches F G the whole of the light from F G will pass through. Therefore, by using an analyser no extinction of light takes place in any position.

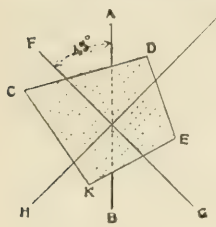


FIG. 143.

But another property of the crystal may come into play. It was mentioned in describing the action of double refraction that one of the two rays was retarded in its progress through the crystal to a greater extent than the other. Supposing that a beam of polarised light has been divided into two by a plate of crystal and that an analyser above the crystal is placed with its principal section at 45° to these two rays, it converts a portion of each of these two rays so that they are again vibrating in one direction; but one of these components has been retarded more than the other by the crystal, and if the crystal is of the thicknesses required, one ray will lag behind the other to the extent of $\frac{1}{2}$, $1\frac{1}{2}$, or $2\frac{1}{2}$ wave lengths, and the two rays, when they unite in the analyser, will interfere, as described in the explanation of diffraction on page 59. They will extinguish one another if they are of the same intensity and partially extinguish one another if they are of unequal intensity; but, as white light consists of light of all colours each of which is of a different wave length, it can only be one colour which is in a condition to interfere, and thus the light which passes

through the analyser will not be entirely extinguished, but will be deprived of one colour and the remaining light will not be white but of the complementary colour to that which is extinguished. Thus another test to the action of a crystal can be applied by means of which it can be recognised.

If a wedge of a known crystal, such as quartz, is placed side by side with such a mineral and the colour compared, or if it be placed over it till the colour is neutralised, the behaviour of the crystal can be estimated.

For this purpose petrological microscopes are provided with a slot in the eyepiece in which a graduated wedge of quartz can be slid backwards and forwards and the effect noted.

It may be asked why this effect of interference causing the appearance of colour in a crystal should not be seen without the use of an analyser. The explanation is that light cannot interfere unless it is vibrating in the same direction; and it is only after the analyser has taken a portion of the two rays which are at right angles to each other and resolved them into one direction that interference can take place. It can be understood that a wind blowing from north to south can extinguish the effect of a wind blowing from south to north, but would not do so to a wind blowing from east to west. This introduces a different phenomenon which is called circular or elliptical polarisation. If an ether particle (Fig. 144 X) is vibrating in the north and south direction, due to a gust of south wind, and if when it has reached the point N it receives a gust of west wind in the direction of the arrow, it will be given a circular or elliptical motion; it is always being acted upon by a force which makes it endeavour to return to its original position at X, and therefore this circular or elliptical motion will be more or less around its position of rest at X; the plane vibration has been converted into a rotary vibration which gives rise in the examination of crystals to a further series of colour effects which are beyond the scope of this book to describe, but which are of great service in the identification of minerals.

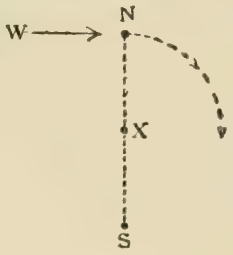


FIG. 144.

A quarter-wave plate used in petrological microscopes is a plate of thin mica of such a thickness that one of the two waves which it transmits has been retarded one-quarter of a wave length more than the other, and upon emergence into the air the plane vibration has been changed by this means into a circular vibration.

The results produced, due to retardation, are very striking and curious, especially if light is thrown through a crystal at different angles. Suppose Fig. 145 represents a plate of crystal illuminated by a cone of rays A *o*, B *o*, C *o*, D *o*, E *o*. A *o* passes

through a greater thickness than B *o*, and B *o* than C *o*, and therefore, when each of these rays has been divided into two and resolved again into one by the analyser, they will each be in a different condition as regards interference, and the result will be that at the position where they are brought to a focus they will form an elaborate coloured pattern.

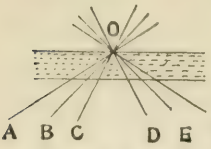


FIG. 145.

Petrological microscopes are provided with a substage condenser or converging system of lenses, above the polariser and immediately below the stage of the microscope. It throws a convergent beam of light upon a crystal placed on the stage; and if a high-power microscope object-glass be used in the nosepiece of the microscope, the interference pattern referred to will be formed in the back focal plane of the object-glass very close to its back lens.

This pattern cannot be seen by looking through the microscope in the ordinary way, because the plane where it is formed is not in focus. If the eyepiece of the microscope is removed it can be seen by looking down the tube, but it is very small. If a lens (generally called a Bertrand lens) is placed at the lower end of the draw-tube, this lens, combined with the eyepiece, turns the draw-tube into a complete low-power microscope; and if this be slid up and down it can be focussed upon the back focal plane of the microscope object-glass and a magnified image of the pattern will be seen.

Another method of obtaining an enlarged image of the pattern is by placing a high-power magnifier (called a Becke lens) over the top of the eyepiece and focussing it until a sharp image of the Ramsden circle or eyepoint is obtained. This Ramsden circle is a conjugate image of the back of the object-glass, and any pattern at the back of the object-glass will reappear in the Ramsden circle.

Light is polarised in most cases when it is either reflected or refracted. The degree to which it is polarised varies according to the angle at which it meets the reflecting or refracting surface. Suppose a ray of light, A O, Fig. 146, meets a glass surface, X O Y, at the point O, a portion of the light is reflected in the direction O B and a portion is refracted in the direction O C. There is a tendency to polarise both the reflected and the refracted light. The reflected beam O B has a tendency to vibrate chiefly in a plane at right angles to the plane of the paper, and the refracted light O C to vibrate in the plane of the paper. The whole of the light is not polarised, but the proportion polarised increases to a maximum when the reflected ray O B is at 90° from the refracted

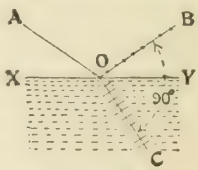


FIG. 146.

ray O C, which angle therefore varies as the refractive index. The angle of incidence of the greatest polarisation is called the polarising angle. It is about 53° for water, 56° for crown glass, 58° for flint glass, and 67° for diamond.

When a beam of light has been reflected or refracted at a surface of glass it consists of a portion of polarised light and a portion of unpolarised light; if that be again refracted, the polarised light will not be changed, but a proportion of the unpolarised light will be again partially polarised; and thus, by a succession of refractions or reflections, a beam of light can be obtained which is almost completely polarised.

Upon this principle various polarising appliances have been made, the simplest being a single surface reflector consisting of a plate of black glass polished on one side only and placed at the polarising angle (Fig. 147); the more perfect form being a series of transparent parallel glass plates set at the polarising angle in which the light may either be reflected from them or refracted through them (Fig. 148).

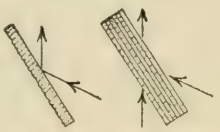


Fig. 147. Fig. 148.

The reflection of light within a dense material when the surface separates it from a lighter material has special points of interest.

Suppose A B, Fig. 149, represents a surface with glass below it and air above it. If a ray of light, C O, strikes the surface from glass, light passes through the glass in a direction O D, and also is reflected along O E and a polarisation of some of the light takes place, reaching a maximum when E O D is 90°; but if the light at, say, F O strikes the surface beyond the critical angle it is all reflected and a curious phenomenon takes place.

It would almost appear as if that portion of the light which would have passed out of the glass into the air if it had not struck the surface beyond the critical angle had entered the surface sufficiently to become polarised and had been slightly retarded in its endeavour to get through; at any rate, when it is reflected along with the ordinary reflected ray it is out of phase and acts upon the reflected ray as if it had been retarded by a crystal and causes circular or elliptical polarisation. If a plane polarised ray is reflected inside a highly refracting medium, it no longer remains a plane polarised ray, but is more or less elliptically polarised according to the angle of refraction; and it is due to this that it is possible to see objects brilliantly illuminated on a dark field, between crossed Nicol prisms or tourmalines, as described on page 130.

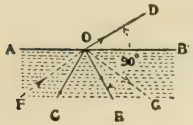


Fig. 149.

The main requirements of a petrological microscope follow from the above short study of the principles of polarised light. A simple form of the instrument is described in *The Microscope*,

a Simple Handbook, and a more complete research instrument is described on page 174. The more important petrological appliances are described below.

The Polariser may be a Nicol prism or any other form of polarising prism. It may be a plate of tourmaline, a plate of black glass placed at the angle of polarisation, or a bundle of thin plates of glass. It should be mounted so that it can be readily swung out of the optic axis in order to compare rapidly the effect of polarised versus unpolarised light. It should also be capable of rotation on the optic axis. The two latter requirements render the use of a black glass reflector or a bundle of thin plates inconvenient, and, moreover, both of these polarisers allow a considerable amount of unpolarised light to pass through. Any of the various forms of prisms made from Iceland spar are entirely satisfactory, but due to the difficulty in obtaining large pieces of clear Iceland spar such prisms are generally small. The Nicol prism is the most usual form, but it is about three times the length of its aperture, rendering a large-aperture prism bulky; such a prism requires a large space between the stage and the mirror of a microscope to accommodate it. The most satisfactory polariser is an Ahrens prism, which has a length about $1\frac{1}{3}$ times its aperture. It is somewhat costly because of the waste of spar that is involved in cutting it.

A plate of light green tourmaline about 3/4 inch square is a perfect polariser for many purposes, but is difficult to obtain in such a large size. The polariser should be mounted on a swing-out arm below the stage of the microscope, but at a distance sufficiently far away to allow of a wide-angle condenser between it and the object. If the polariser has a sufficiently large aperture, and if there is sufficient room between the stage and the mirror, as in the Radial Research microscope, the best arrangement is to have the polariser at a considerable distance below the stage, leaving room for a full-size wide-angle achromatic condenser with iris diaphragm, tray for stops, and full focussing adjustments between it and the object. The prism or tourmaline should then have a clear aperture of about 3/4 inch.

The rotating motion of the polariser should have four spring clicks that enable its position to be felt at each 90°, or it should have only 90° rotation with a definite stop at each end of its travel. It is convenient to have a divided scale of degrees, though it is not often that positions except at each 90° require to be registered.

If a polariser of small aperture is used it may still be employed to fill the whole of a large aperture condenser with light, if it is attached to the lamp instead of to the microscope or placed at some considerable distance below the condenser. This is inconvenient on a purely petrological microscope, and specially small wide-angle condensers are generally supplied to work with

small Nicol prisms for examining the rings and brushes of crystals.

It is convenient to have a fitting for a slide below either the polariser or the condenser to carry a movable slit for the Becke shadow test.

The Stage of a petrological microscope must be provided with a rotating motion with a scale of degrees, unless the two polarising prisms are connected together and provided with a motion which rotates the two together upon the principle described on page 174.

If the stage rotates a centring adjustment must be provided, either to the stage itself or to the nosepiece of the microscope, so that the rotation may take place accurately around the optic axis of the microscope. No microscope is made so rigidly and with such perfect alignment that the required degree of accuracy could be maintained for long or which would permit of the interchange of object-glasses and apparatus without re-adjustment.

The best position for such an adjustment is on the stage, as when fitted to the nosepiece it is generally damaged by the constant screwing and unscrewing of object-glasses and illuminators. The nosepiece of a microscope should be as rigid as possible to maintain optical alignment on the optic axis.

The Analyser may be a Nicol prism, a Thompson prism, or an Abbe prism, or a plate of light green tourmaline. It must be placed at some position above the object in the body of the microscope. It is sometimes carried in a slide immediately above the object-glass, sometimes between the lenses of the eyepiece, and sometimes between the eyepiece and the eye.

The position above the eyepiece has great advantages. It enables quartz wedges, various doubly refracting plates, micrometers, and other apparatus to be introduced in the focus of the eyepiece so that they are between the polarising prisms and are in focus at the same time as the object. It enables the analyser to be rotated and does not introduce any serious deterioration of the image due to imperfections in the manufacture of the prism, but unless a plate of tourmaline can be used it is so thick that the eye cannot be placed in the eyepoint or Ramsden circle of the microscope, and the field of view is somewhat restricted. A prism made of Iceland spar cannot be made with perfect surfaces, because the material is so soft and has always some slight imperfections. Such errors are of no consequence if they are not magnified, but when the prism is placed immediately behind the object-glass they are highly magnified and may somewhat impair the quality of the image. The Abbe prism in the eyepiece is practically perfect, as its surfaces can be made more accurately, but it can only be used with a particular eyepiece,

and under certain conditions gives rise to a second image of the cross wires formed by the extraordinary ray. There is no doubt that a colourless plate of tourmaline would be the most perfect analyser; and as occasionally they are to be met with almost free from colour it is probable that they will eventually come into more general use.

The analyser should be mounted, like the polariser, with a means of rapidly moving it in and out of the optic axis, and should have a similar rotating motion. When it is placed in the eyepiece or above the eyepiece, both these motions can be readily provided; when it is immediately behind the object-glass, it cannot be made to rotate so easily.

If the analyser is immediately behind the object-glass the focus of the microscope is slightly altered when the prism is moved in and out of the axis, because the insertion of the prism introduces a thick block of highly refracting material in the path of the rays of light. This can be compensated by adding a low-power lens to the mount carrying the analyser, but this is not desirable, as it influences the correction of the object-glass. It can also be compensated by sliding a thick parallel plate of glass into the optic axis as the analyser slides out, but this is not recommended, and it is better to compensate for the slight change in focus by a movement of the focussing adjustment.

The examination of the interference patterns of rings and brushes by convergent light has been alluded to. It is a great convenience to be able to introduce the apparatus for effecting this without upsetting any of the adjustments of the microscope. In the Radial Research microscope the condensing lenses can be slipped in and out of the substage dovetail. The Bertrand lens can be slid in and out of the optic axis, or the Becke lens can be folded in and out of position on a holder, as illustrated on page 145. The chief advantage of the Bertrand lens over the Becke system is that the cross wires or a micrometer in the eyepiece are still in focus when the Bertrand lens is introduced, which, if the Becke lens is used, is not the case and a special micrometer in its focus is required. Also a higher magnifying power can be obtained with a Bertrand lens. On the other hand, with a small and moderate-priced petrological microscope, the Becke lens system above the eyepiece is more convenient.

Cross wires in the focus of the eyepiece are necessary for the measurement of the angles of crystals, and they are provided in two manners. A plate of glass, with lines ruled upon them, is a popular method, but it has the disadvantage that it collects dust which shows in the field because it is in sharp focus, and that the two extra reflecting surfaces may under certain conditions produce a glare which is troublesome in taking photomicrographs, even if it is not very apparent in visual observations. A pair of fine cobwebs or fibres stretched across a diaphragm are to be

preferred, though they are more liable to damage and must be treated with care.

Quarter Waveplate.—This is a plate of mica of such a thickness that the retardation of one of the two rays into which it decomposes the light is a quarter of a wave length behind the other. It is either cut with rectangular edges parallel to the two directions of vibration or such directions are marked upon it. It is used to compensate similar and opposite effects produced by specimens being examined on the stage of the microscope, for the examination of the ring and brush interference patterns of crystals, and several other purposes.

Unit Retardation Plate.—A selenite plate giving red of the first order will produce a retardation of one wave length, and is used for similar purposes.

Quartz Wedges (Fig. 150).—These are made in various forms, and are mounted on a slip of glass which can be slid in and out of the optic axis between the analyser and the polariser. Petrological microscopes in which the analyser is in the eyepiece or over the eyepiece are provided with a slot at 45° to the axis of the crossed Nicol prisms, at a position that is in the focus of the top lens of the eyepiece. In cases where the analyser is immediately behind the object-glass the quartz wedge can be used on the stage of the microscope over the specimen that is being examined if a very low-power object-glass is employed. The simple quartz wedge is a strip of quartz cut parallel to the axis of the crystal, which is the thickness of a knife-edge at one end and gradually increases in thickness up to the other end. The appearance caused by inserting the quartz wedge between the polariser and analyser is a series of coloured bands in succession at right angles to the length of the wedge, due to the difference in the retardation of the light as it passes through different thicknesses of the quartz. There are a succession of somewhat similar sets of colours, each set being called an order ; and a quartz wedge shows from three to eight orders according to the steepness of the angle of the wedge ; the position of these orders is sometimes indicated by graduations on the wedge. By the insertion of such a wedge over a mineral that shows colour due to interference the colour can be neutralised at some position of the wedge and a black band will appear. The position of this band is called the point of compensation. By this means the amount of double refraction of a mineral can be ascertained. As the knife-edge of the wedge can never be made without thickness the simple quartz wedge cannot extend exactly to zero. To obviate this a special wedge is made, cemented upon a thin plate of selenite

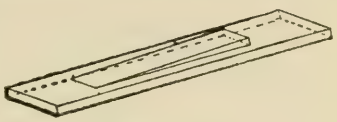


Fig. 150,

arranged to partially compensate some of the thickness of the quartz wedge; the zero position is moved by this means slightly towards the thick end of the quartz and a dark band appears at the compensation point. This zero position is inoperative, and specimens seen through this dark band are not affected till the wedge is moved one way or the other.

Dr. Evans' Double Quartz Wedge.—This consists of two wedges placed side by side and ground to the same angle. One wedge is so cut that its length is parallel to the optic axis of the crystal, the other that its breadth is in this direction. It is very convenient, as it shows in one operation the effect of inserting the wedge at 45° in two directions; for instance, north-west and north-east.

The Babinet Compensator (Fig. 151).—This consists of two quartz wedges cut to the same angle, one over the other, one of which is fixed and the other movable by a micrometer screw. A Ramsden eyepiece is contained in a fitting above the wedges and the apparatus is inserted in the microscope in place of the ordinary eyepiece. The two quartz wedges are cut at different angles of the crystal, so that the directions of vibration lie at right angles to each other. The compensator is placed in the microscope so that the wedges are at 45° to the plane of polarisation of the polariser, and an eyepiece analyser is placed over the eyepiece of the compensator. Two cross lines are engraved upon the upper surface of the fixed quartz wedge. When plane polarised light enters the two wedges in a plane, say north and south, the compensator lower wedge will decompose the plane polarised ray, so that the ordinary ray will vibrate in a north-south direction and the extraordinary ray in an east-west direction. The upper wedge will act in converse manner, the ordinary ray being east-west and the extraordinary ray north-south. If the position of the wedges below the cross lines is such that the thickness of the wedges is equal they will compensate each other, while a very slight movement of the lower wedge one way or the other will produce the effect of a thin wedge.

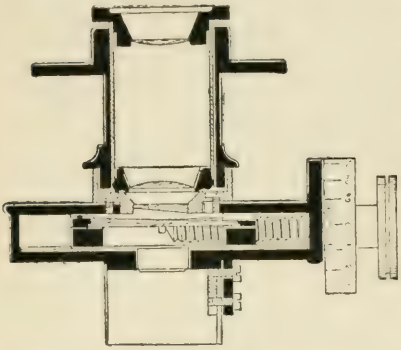


FIG. 151.—Babinet's Compensator.

Klein's Quartz Plate. — The position of greatest darkness obtained by crossing the polariser and analyser of a petrological microscope is sometimes difficult to set with great accuracy, and

several appliances are supplied to assist this determination where great accuracy is required. The Klein's plate is a parallel section of quartz cut at right angles to the optic axis, of such a thickness that it appears between crossed Nicols of a violet tint which changes its colour very rapidly for a slight rotation of the Nicols.

Bertrand Eyepiece (Fig. 152).—This is a more sensitive means of observing slight changes of the rotation of the plane of polarisation. It consists of an eyepiece over which an analyser can be placed, and in the focus of the top lens are four plates of quartz cut into 1/4 of a circle and cemented together. Two opposite segments are made of right-handed quartz, the two others of left-handed quartz, so that at the lines of junction there is always right-handed quartz on one side and left-handed quartz on the other. As the property of these two kinds of quartz is to rotate the plane of polarisation in opposite directions, any change shows an alteration on both sides of the dividing line and it forms an unusually sensitive instrument. It is a modification of the Bi-quartz, which consists of only two instead of four plates.

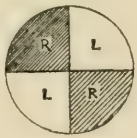


Fig. 152.

Stauroscopic Plate.—This consists of a parallel plate of Iceland spar cut at right angles to the optic axis. It is inserted between the analyser and the eyepiece where it shows the characteristic black cross interference cross. The introduction of crystals upon the stage of the microscope in general causes a distortion of the black cross as the crystal is rotated.

Savart Plate.—This is used for detecting very small amounts of polarised light which may be present in otherwise unpolarised light. It consists of two plates of quartz or Iceland spar, both of the same thickness and both cut at 45° to the optic axis but turned at right angles around an axis normal to their surfaces and cemented together. If such a plate is placed in front of an analyser the presence of any polarised light will be detected by the appearance of parallel dark bands across the field.

Double-Image Prism (Fig. 153).—This consists of a prism of Iceland spar or quartz cemented to a prism of similar shape made of a glass that has the same refraction as the spar or quartz, as regards its effect upon the ordinary ray, towards which the combined prism acts as a parallel plate of glass; but the extraordinary ray is more highly refracted, and it acts upon this as a prism, with the result that a double image is produced, the light of the two images being polarised in directions at right angles to each other. This when used in place of an analyser enables the colours produced by minerals which give coloured images, due to pleiochroism or dichroism, to be examined with greater

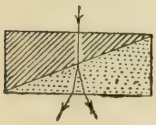


Fig. 153.

accuracy than by revolving them between crossed Nicols, because the colour of the two images are seen side by side and can be carefully compared. The prism fits over the eyepiece in place of the analyser, and a brass plate with a series of different-sized holes is slid into the slit in the eyepiece in the focus of the top lens. A hole can be selected of the size required to make the two images appear side by side, almost touching, or to somewhat overlap. Double-image prisms of various kinds are made giving different degrees of separation of the two images, and in some, one image remains stationary while the other rotates round it upon revolving the prism; in others, both images rotate in opposite directions.

FIG. 154.—Dichroiscope.

Dichroiscope (Fig. 154).—A small instrument for testing gems, which can be carried in the pocket, is made upon this principle. At one end is a lens and at the other is a small rectangular opening in the focus of the lens, and between the two is a double-image prism. The mineral to be examined is held in front of the rectangular aperture, or is attached to it by wax. A more elaborate model (Fig. 155) is provided with a revolving holder to carry the object. A small cup filled with wax is carried on an arm that can be raised or lowered and rotated in two azimuths. It can be swung out of the field for fixing the object in position.

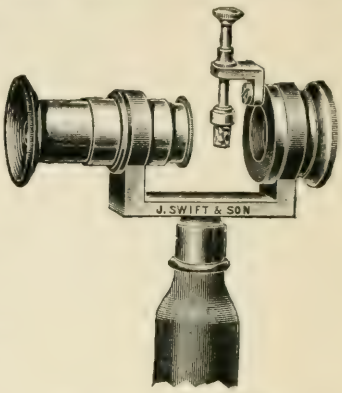


FIG. 155.—Dichroiscope.

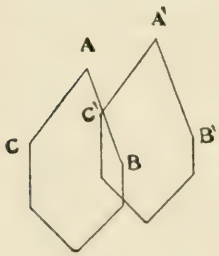


FIG. 156.

Leeson's Goniometer. — The double-image prism is also used for making an accurate measurement of the angles of crystals or other objects. The Leeson's goniometer fits over the eyepiece like an analyser, and is provided with a flange divided in degrees upon which the rotation of the prism can be measured. Fig. 156 indicates a crystal as seen through the goniometer; two images, A B C and A′ B′ C′, will be seen, which revolve around one another as the prism is revolved. If the edge A B is brought into the position that it is in a continuous line with A′ B′, and the prism is then revolved till the line A C is in a

continuous line with the edge A′ C′, the rotation required to make this change measures the angle C A B.

Simple Goniometer Eyepiece.—A simple form of goniometer eyepiece consists of a revolving eyepiece with cross wires and a divided scale to measure the rotation (see page 186, Fig. 122). To use this, one of the lines is placed along one edge and then rotated till it is parallel to the other edge of the crystal to be measured. It is not so accurate as the Leeson's goniometer, but is a serviceable apparatus.

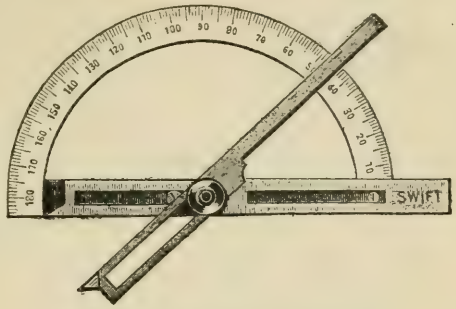


FIG. 157.—Contact Goniometer.

Contact Goniometer (Rome de l'Isle) (Fig. 157).—This instrument is designed for measuring the angles of the faces of crystals by contact. It has a 3 inch diameter half-circle of divisions, graduated in degrees, and has adjustable centres.

Small Stage Goniometer (Fig. 158).—This is an instrument that can be clamped to the stage of a microscope. It consists of a horizontal rotating rod which carries at its end either a pair of forceps or a needle point. A grain of sand or crystal may be held in the forceps or be attached to the needle point by a small portion of wax and be examined either dry or immersed in a fluid in the cup surrounding the forceps or needle point. The rotation of the mineral can then be read by means of a vernier to 5′ of arc.

Stage Goniometer (Bowman with Sir H. Miers' improvements) (Fig. 159). — This is clamped to the stage of the microscope. It is fitted with complete arrangements for adjusting and centring a crystal. The crystal, mounted on the end of a steel pin, can be brought to coincide with the turning axis and adjusted so that one of its edges is parallel to this while it remains under observation in the microscope field. It is especially suitable for minute crystals examined with high powers, particularly those which show twin lamellation, etching pits, etc. The crystal can

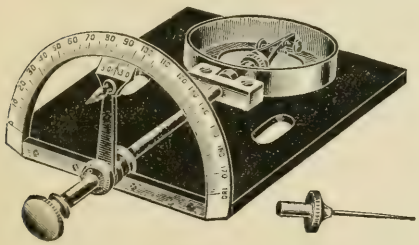


FIG. 158.—Stage Goniometer.

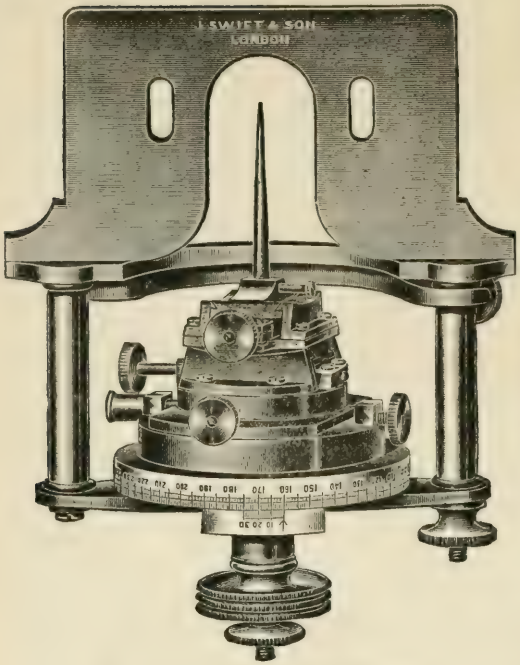


FIG. 159.—Bowman Goniometer.

be immersed in a drop of fluid hanging between the front lens of the object-glass and the front lens of the substage condenser. The divided circle reads by a vernier to 1′.

The Herbert Smith Goniometer (Fig. 160).—This is a simple form of goniometer for measuring the angles of crystals. The object holder allows of the setting up of a crystal edge parallel to the axis of the circle, so that all necessary measurements can be made without the readjusting of it on the wax by which it is attached. The circle is 5 inches in diameter and reads to 1′ by a vernier. A black glass mirror is fixed to the base, which has complete motions but can be clamped in any position.

Improved Wollaston Goniometer (Fig. 161).—This instrument is intended for more exact research work. It reads by means of a vernier to 1′ and is provided with clamp and tangent screw fine adjustment for rotation. It is provided with the ordinary centring and adjusting head, on which the crystal is set up by means of four screws. The base is provided with three levelling screws. A mirror can be used for viewing a distant signal, or a

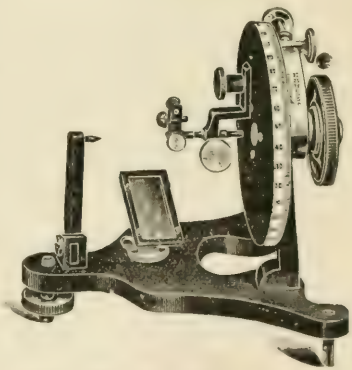


FIG. 160.—Smith Goniometer.

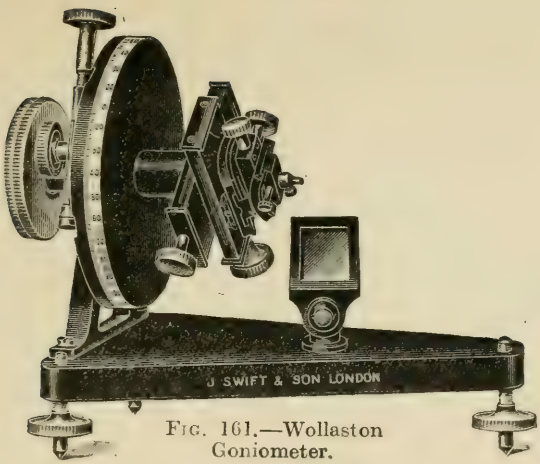


FIG. 161.—Wollaston Goniometer.

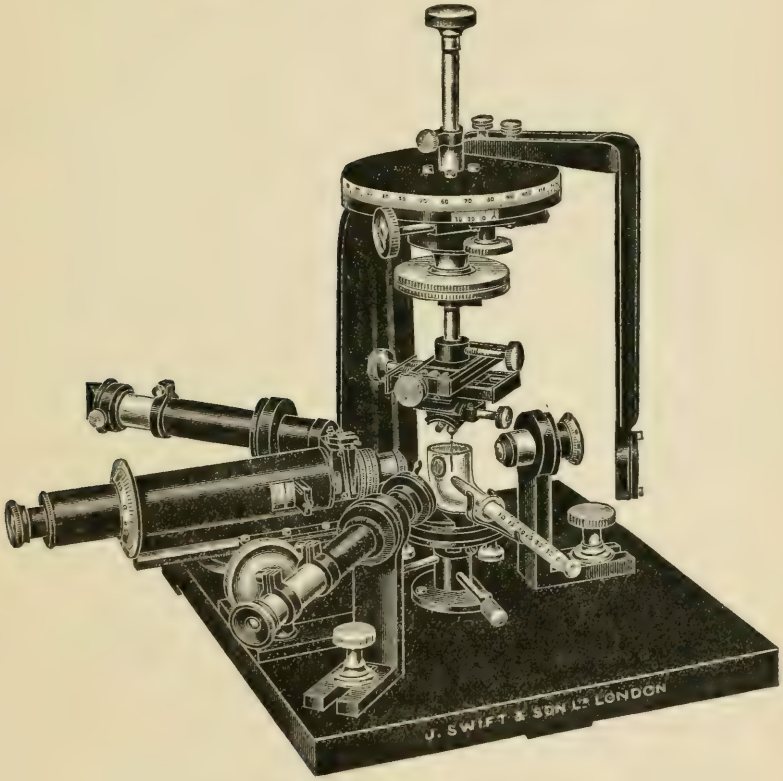


FIG. 162.—Hutchinson Goniometer.

telescope and collimator can be fitted if desired, in which case the former has cross webs to the ocular and an extra lens to swing over the objective to convert the system into a low-power microscope, while the latter carries the Websky signal.

Dr. Hutchinson's Universal Goniometer (Fig. 162).—This instrument is a goniometer of the suspended type, chiefly intended for the examination of small crystals. It can be used: (1) as an ordinary goniometer for the measurement of angles; (2) as an axial angle apparatus; (3) as a Kohlrausch total-reflectometer; (4) for determining refractive indices by the prism method.

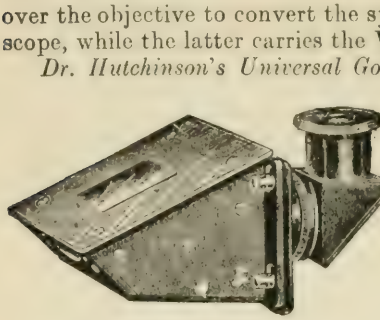


Fig. 163.—Smith Refractometer.

The circle is 5 inches diameter and reads by vernier to 1′. It has a clamp and tangent screw. The usual centring and adjusting head is carried on a steel axis passing through the centre of the circle, which can be clamped at any convenient height. The base plate, which is 11 inches square, carries telescope and collimator, a completely equipped mineralogical microscope with polariser, analyser, Bertrand lens, objectives in centring changers, etc., and an adjustable table with levelling screws.

The long arm shown in the figure suspended from the circle is detachable, and is used for carrying the telescope when refractive indices are to be measured by the prism method.

The instrument is useful for other experimental work in which a graduated circle is required, as other apparatus can be clamped to the base plate in any convenient position.

Herbert Smith Refractometer (Fig. 163).—This instrument measures refractive indices from 1·3 to 1·79 for translucent solid substances or fluids. It is largely used for the identification of gems, stones, and other minerals. The substance to be measured must have one flat polished surface, which is kept in optical contact with the plain glass surface on the top of the instrument by means of a drop of fluid of high refractive index. Daylight, or preferably monochromatic illumination, is thrown from the window on the under side, when the refractive index of the substance can be read off direct, without calculations, through the

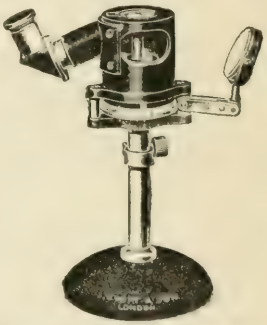


Fig. 164.—Gem Refractometer.

eyepiece. It reads to the second place of decimals, and with monochromatic light can be approximated to the third place.

Gem Refractometer (Fig. 164).—The refractive index of the substance under examination is read off direct on a scale in the telescope and is correct to 2 or 3 units in the third place of decimals. The range extends from 1·4 to 1·79. To facilitate the measurement of double refracting substances a circle divided to every 5° rotates a dense flint hemisphere within the instrument. The hemisphere is surrounded with a light-tight casing provided with a shutter, which allows of illumination by reflected light or light at glancing incidence. The aperture at the side of the casing is for cleaning the hemisphere.

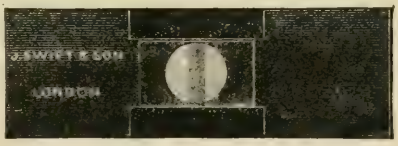


FIG. 165.—Wright's Refractometer.

Wright's Stage Refractometer (Fig. 165).—With this instrument the refractive index of a fluid may be ascertained on a microscope fitted with a Bertrand lens and a micrometer scale in the ocular with an accuracy of one or two units in the third place of decimals. It consists of two parallel glass plates of very high refractive index, each of which has an edge bevelled at 60°: one of them with a polished and the other with a greyed surface. In use, the former is placed with its polished bevel over and in contact with the greyed bevel of the latter ; a drop of the liquid to be measured is placed between them and its refractive index ascertained by observing the position of the limiting refracted ray between the light and dark fields. The scale is calibrated empirically by the use of substances of known refractive indices. The best object-glass for use with this is one of 16 mm. focus.

Clarici Cell (Fig. 166).—This consists of a glass cell cemented upon a 3 × 1 glass slip, and in the centre of the cell a glass prism is cemented. A pair of cross lines are ruled on the glass slip below the prism, with the result that one of the lines appears to be displaced by the prism. If the cell be filled with fluid, and a cover-glass be placed on the cell to ensure a parallel layer, the displaced line will be altered in position according to the refractive index of the fluid. This is examined, without a Bertrand lens, with a micrometer in the eyepiece, and the value of the division can be calibrated by the examination of three or four fluids of known refractive index.

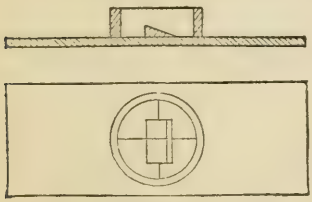


FIG. 166.—Clarici Cell.

Crystal Refractometer (Fig. 167).—This instrument is designed for the measurement of the refractive indices of both solids and liquids ; it yields an accurate reading to the third place of decimals with an approximation in the fourth.

The apparatus consists essentially of a dense glass hemisphere capable of rotation about a vertical axis, and a telescope attached to a divided circle, the axis of which bisects the plane of the hemisphere.

The range of reading is limited by the refractive index of the glass of the hemisphere ; this in the standard instrument lies, according to the different meltings of glass used, between 1·79 and 1·80 for the D line of the spectrum. The instrument is, therefore, available for use with all the principal minerals, including corundum, etc.

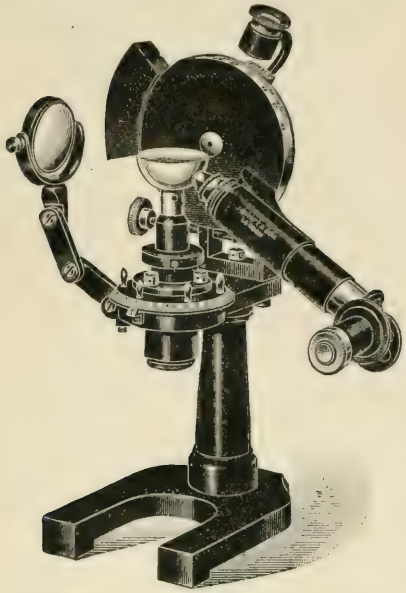


Fig. 167.—Crystal Refractometer.

An extra-dense hemisphere, having a refractive index above 1·90 for the D line, can be supplied to special order, but as this glass is, of necessity, somewhat soft mechanically and liable to tarnish it is not recommended for general work.

Observations must always be made with a monochromatic source of light, the sodium flame being that most generally adopted.

For the measurement of a liquid all that is requisite is to place a drop of it on the centre of the hemisphere. A solid must have a flat surface in contact with the hemisphere and the two must be brought into optical contact with a film of some liquid of higher refractive index than that of the object under examination. Generally speaking, the thinner the film the more accurate the reading, so it is as well to press the object down gently on the hemisphere, at the same time taking care not to injure the glass surface. The most generally adopted media are monobromnaphthalin, *n*.D.1·66, and methylene-iodide, *n*.D.1·75 ; the refractive index of this latter can be raised to 1·78 by the addition of sulphur, of which it is a solvent.

The refractive index of the substance examined is deduced

from the angle of total reflection of a beam of light in the hemisphere in contact with air, compared with that of a similar beam in the hemisphere when in contact with the substance ; this may be expressed as :—

$$n \frac{\sin \theta_2}{\sin \theta_1},$$

θ_1 being the critical angle of the glass in contact with air, and θ_2 the critical angle when in contact with the substance.

These readings are made by sending a narrow cone of light, by means of the adjustable condensing lens, along the plane surface of the hemisphere at glancing incidence. The shadow denoting total reflection is picked up and the webs in the ocular coincident with it by rotating the telescope, together with its divided circle, about the hemisphere. This is effected approximately by hand in the first place ; the circle is then clamped and the final setting done by means of the fine adjustment at the side. The reading θ_1 in the above formula is obviously taken before the substance to be examined is placed in position.

Another method is to replace the condensing lens by a mirror and to throw a beam of light upwards at a moderate angle through the hemisphere on to the lower surface of the substance to be determined ; a light and dark field is seen in the telescope as before, and similar readings are taken.

For the accurate setting of an object on the hemisphere, and its examination when in that position, an additional lens system is provided ; this, when inserted in the eye end of the telescope, converts it into a low-power microscope. An analyser, with a circle divided to every 45° and clicked at 0° and 90°, is provided for the measurement of both rays of double-refracting minerals, etc.

Tank Refractometer (Fig. 168).—This apparatus, built to the design of Mr. A. F. Hallimond, M.A., and Dr. H. H. Thomas, affords a convenient means of determining the refractive indices of liquids in bulk. It is particularly useful for accurately and expeditiously preparing standard fluids for testing the refractivity of minerals, etc. The results given are accurate to within one unit in the third place of decimals, and are practically immune from errors of adjustment

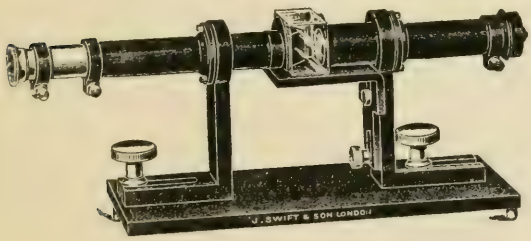


Fig. 168.—Tank Refractometer.

and reading. The optical arrangement is similar to that of a direct-vision spectroscope, light from the collimator being deviated at the two side faces of a standard right-angled prism immersed in the liquid to be determined. The distance between the two images of the slit which are seen on the scale in the eyepiece of the telescope measures the difference in index between the liquid and the standard prism. To cover the ordinary series of liquids for mineral determinations, ranging from approximately 1·46 to 1·76, four standard prisms are included; a fluorite prism giving readings down to below 1·40 and an extra-dense prism to above 1·80 can be supplied if required. A full description of the original instrument appeared in the *Mineralogical Magazine*, March 1921, vol. xix, No. 92, pp. 124–129.

Spectroscope for Petrological Microscopes (Fig. 169).—This

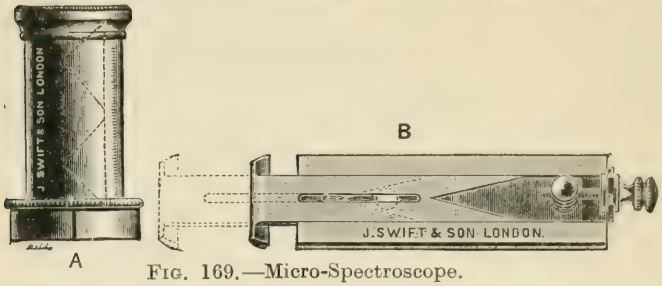


Fig. 169.—Micro-Spectroscope.

modified form of spectroscope can be used on most petrological stands. It will be found particularly useful when examining minerals of the monazite class, the bands of which are seen best with a prism of moderate dispersion.

The prism (A) is mounted to fit over the ocular, while the brass plate (B) is inserted in the slot cut through it. This plate is provided with an adjustable slit, which can be varied in length by a slide with a V-cut at one end. There is a small circular hole pierced through the plate so that the object can be located before the slit is pushed into position.

The Shand Recording Micrometer (Fig. 170).—This instrument

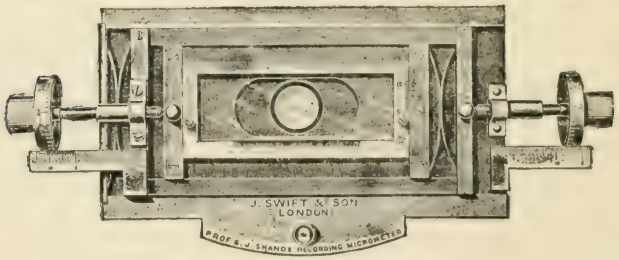


Fig. 170.—Shand Micrometer.

is attached to the stage of a petrological microscope, and by its means the percentage of a particular mineral in a section can be accurately estimated without fatigue. It consists of two slides within one another which both record independently the lateral movement of a slide placed within the inner frame by micrometer screws and drums which read to ·01 mm. The method of use is as follows: The section of rock being placed in the apparatus, the edge of one of the particles of the mineral to be estimated is placed against the cross wire in the eyepiece; it is then moved by the left-hand screw until the other edge of the particle is against the cross wire; the specimen is then moved by the right-hand screw till the next particle touches the cross wire. It is then moved by the left-hand screw till the other edge of the particle is against the cross wire. This process is continued over the length of the slide, and at the end the total motion of the left-hand screw, compared with the total motion of the slides—namely, the motion of the right- and left-hand screws added together—gives the percentage quantity of the material present. Several readings in different parts of the slide give a more accurate average.

LIST OF APPARATUS

THE following is a list of the apparatus mentioned in this book, which has not been described in *The Microscope, A Simple Handbook*. It can be obtained from R. & J. Beck, Ltd., 68 Cornhill, London, E.C.3.

No.	Page	
3278	157	Glass plate to drop into eyepiece ruled with 50 divisions 1/20 mm. each.
3276	157	Stage micrometer ruled 1/100 and 1/1,000 inch.
3277	157	Stage micrometer ruled 1/10 and 1/100 mm.
349c	153	Grayson's Rulings ruled in 10 bands, 1/1,000 to 1/10,000 inch.
349d	153	Grayson's Rulings ruled in 12 bands, 1/5,000 to 1/60,000 inch.
349e	153	Grayson's Rulings ruled in 12 bands, 1/10,000 to 1/120,000 inch.
3276a	158	Micrometer eyepiece with one fixed cobweb, and one cobweb traversed by micrometer screw, reading to 1/100 mm.
3623s	158	Microscope for measuring Brinell test impressions.
3176	159	Microscope for measuring wire and fibres by projection, including 100-c.p. "Pointolite" lamp and resistance for direct or alternating current, condensing lens, substage illuminator, adjustable wire holder, 8-mm. apochromatic object glass, compensating eyepiece, mirror, ground glass screen, movable scale, complete.
3187	161	Micrometer measuring microscope with micrometer screw travelling microscope reading to ·01 mm., with 4-inch range and cross-motion with scale moved by rack and pinion, 16-mm. object-glass and eyepiece with cross-lines.
3258	186	Goniometer eyepiece for use with above.
3188	161	Telescope object glass for using micrometer microscope as cathetometer.
3030s	165	Swift screw measuring microscope with 1½-inch object-glass, cross-webbed eyepiece, complete set of chucks for micrometer screws, etc., in case, reading in mm.
3031s	165	Swift screw measuring microscope as above, but reading in parts of inch.
3032s	165	Attachable arms for carrying large objects.
3033s	165	Extra object-glass 2-inch focal length.
3034s	165	Extra object-glass 1-inch focal length.
3035s	165	Extra object-glass ⅔-inch focal length.
3190	167	The Radial Research Microscope complete stand with coarse and fine focussing adjustment, focussing stage, focussing and centring substage, complete with adjustments as follows: (*a*) Square stage with gap in front, vertical and lateral mechanical motions with vernier scales.

No.	Page	
		(*b*) Substage with three dovetailed slides for condensers and illuminators, with two dovetailed slides for colour screen, patches and other apparatus, and including iris diaphragm. (*c*) Bracket with double extension draw-tube on bar with rack-and-pinion motion and divided scales. (*d*) High-power binocular body on bar with rack-and-pinion motions, without eyepieces. (*e*) Greenough binocular body on slide which racks along the main limb of the microscope, without eyepieces. (*f*) Polarising apparatus with large swing-out polariser and swing-out analyser in revolving fittings with apparatus for also turning the two prisms together, thus rendering the circular stage unnecessary. This apparatus includes one eyepiece with cross-lines and slide for introduction of quartz wedges, divided circles, clicked stops for prisms.
3191	167	The Radial Research Microscope stand, as above, but with plain 2-inch body with one sliding draw-tube, stage (*a*), substage (*b*), and no other adjustments.
—	—	Rack-and-pinion double draw-tube.
3192	168	The Radial Research Microscope stand, as above, but with circular rotating mechanical stage with centring adjustments in place of square stage and substage (*b*).
3193	175	The Radial Research Microscope stand, as above, but with high-power binocular body in place of plain 2-inch body, with stage (*a*) and substage (*b*).
3194	167	The Radial Research Microscope stand, as above, but without substage for metallurgical work only, with stage (*a*).
3180	177	Complete microscope table with illuminating and photomicrographic apparatus for Radial Research Microscope, consisting of table standing on four legs with teak top, 63 inches × 25 inches, with upper table 16 inches × 14 inches to carry microscope and illuminants with revolving motion and levelling screws, optical bench carrying electric "Pointolite" lamp in holder with rack-and-pinion vertical motion and horizontal motion, condensing lens, 9 monochromatic screens, double wedge light moderator, mirror and iris diaphragm with complete adjustments, resistance for lamp, ½-pl. 36-inch extension photomicrographic camera on bar with levelling screws which fit 2 sets of sockets in table, one double plate holder, adjustments for actuating fine adjustment of microscope from ground glass of the camera, 3-inch focus "Microstigmar" anastigmat lens for photographing objects direct with small magnification by means of photomicrographic camera, table for holding such objects on the optical bench bar with vertical motion.
3181	177	Outfit as No. 3180, with ¼-pl. camera instead of ½-pl., but otherwise complete.
3182	177	Outfit as No. 3180, but with table 36 inches × 24 inches and without photomicrographic apparatus, but complete with optical bench and apparatus.
3179	179	Optical bench (13 inches long) on two supports with levelling screens with electric "Pointolite" 100-c.p. lamp and resistance, with rack-and-pinion vertical

No.	Page	
		motion and swing horizontal motion to lamp, bull's eye, iris diaphragm, ground glass, double-wedge light moderator, mirror and holders for colour filters, as in outfit No. 3180.
3341	182	½-pl. photomicrographic camera on bar with levelling screws and 1 double plate holder.
3092	195	Beck inverted microscope for metallurgy and chemistry, with coarse and fine adjustments, observing tubes and special vertical illuminator, with motions in two azimuths and lateral motion.
3205	183	Greenough binocular microscope on inclinable stand with stage, mirror, no object-glasses or eyepieces.
3205a	—	Stand as above, with detachable arm rests.
3206	183	Greenough binocular microscope on horseshoe fork to stand upon bench.
3207	183	Greenough binocular microscope on bracket for screwing down to bench.
		Object-glasses in slides for Greenough binocular microscope :
3010	177	59-mm. on slide.
3011	177	49-mm. on slide.
3012	177	32-mm. on slide.
3013	177	16-mm. on slide.
		Eyepieces for binocular microscope :
3260p	177	42-mm. × 6.
3261p	177	25-mm. × 10.
3262p	177	17-mm. × 15.
3185	185	Process microscope with ⅔-inch object-glass, 42-mm. eyepiece with cross-wires, giving magnifying power of 60.
3186	185	Process microscope as above, but with micrometer with 100 divisions instead of cross-wires in eyepiece.
3230a	185	1½-inch object-glass with large working distance.
3258	186	Goniometer eyepiece for measuring angles.
3196	187	Museum microscope stand, monocular, with full adjustments, but without object-glasses or eyepieces, with case.
—	188	Graduated scales to two rack-and-pinion motions reading by verniers.
—	188	Stage with mirror to attach to instrument for converting into an ordinary microscope for use with objects on 3-inch × 1-inch slips.
—	188	Stage as above with swing-out substage, Abbé condenser, and iris diaphragm.
3229	188	Low-power object-glass with very long working distance, giving magnifying power of 5 to 20 and free working distance of about 6 inches.
3208	186	Museum microscope stand as No. 3196, but with Greenough binocular body in addition to monocular body.
3209	186	Museum microscope stand as No. 3196, but with Greenough binocular body in place of monocular.
3177	188	Projection microscope with screw for attaching to ordinary lantern with two eyepieces, 32-mm. and 16-mm. object-glasses, substage condenser and cooling trough, in case.
3178	188	Projection microscope as above with addition of mechanical stage.
3198	189	Horizontal reading microscope with rack-and-pinion focussing motion, raising motion by slide with clamp,

No.	Page	
		rack and pinion giving motion from 13 inches to 21 inches, rotating motion to microscope, levelling screws to stand, one eyepiece and 16-mm. object-glass.
3199	189	Horizontal reading microscope as No. 3198 with spirit level attached to microscope body.
3198	189	Telescope object-glass to screw into body of microscope No. 3198 in addition to microscope object-glass.
3016	189	Tank or aquarium microscope on wooden stand, with rack-and-pinion focussing motion and jointed arm for carrying single lenses or aplanatic magnifiers.
3017	189	Glass aquarium for use with above.
3018	190	Stand for dissecting with jointed arm for holding lenses.
3019	190	Stand for dissecting with jointed arm for holding lenses and rack-and-pinion focussing motion.
3020	191	The Crescent Dissecting Microscope with single swing arm lens holder.
3021	191	The Crescent Dissecting Microscope with double-jointed swing arm lens holder.
3167d	191	Single lenses mounted for dissecting.
3171d	191	Aplanatic magnifiers mounted for dissecting, × 5 and × 12.
3	191	Aplanatic magnifiers mounted for dissecting, × 20.
3004	191	Brücke lens combination for use with dissecting microscope.
3005	192	Non-erecting microscope body for use with dissecting microscope, with one eyepiece and 32-mm. object-glass giving magnifying power of 25. All standard object-glasses and eyepieces will fit.
3006	192	Erecting (prism type) microscope body for use with dissecting microscope, with one eyepiece and 16-mm. object-glass (all standard microscope eyepieces and object-glasses will fit).
3015	192	The Crescent Dissecting Microscope No. 3021 and Greenough binocular body in addition to swinging arm for lenses.
3067	194	Dust and sand microscope with dark ground illuminator and electric torch, one eyepiece, and 16-mm. object-glass giving magnifying power of about 60.
3070	194	Field microscope for mining engineers, with one eyepiece and 16-mm. object-glass in case.
3071	194	Set of grinding and polishing materials for use with No. 3070.
3357	123	Spot lens for dark ground illumination with low powers.
3293	128	Beck high-power focussing dark ground illuminator for use with object-glass 1·2 N.A. with ½-mm. thick slips or ·95 N.A. with 1-mm. slip.
3292	128	Special dark ground illuminator which enables object-glasses with an aperture of 1·3 N.A. to be used.
3326	129	Barnard compressor for use with high-power illuminators.
3326a	129	Circular glass discs for above, ½-mm. thick.
3326b	129	Circular glass discs for above, 1-mm. thick.
3359	97	Beck aplanatic ring illuminator suitable for object-glasses from 40-mm. to 8-mm. focal length.
3359a	97	Beck aplanatic ring illuminator, suitable for object-glass 4-mm. focal length.
3380	184	Ultra-microscopic illuminating attachment consisting of steel bar on three levelling screws with sockets, automatic 5–8-ampère arc lamp, lamp house, collecting lens, adjustable slit with side adjustments, projecting

No.	Page	
		lens, chisel-edge obscuring shutter, microscope object-glass, projector, with complete adjustments.
3381	138	Holder for the examination of moving fluids under the ultra-microscope.

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